



CHALMERS
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Island Operation with Wind Turbines and Batteries (PSCAD)

Coordinated Control Strategy

Master's thesis in 2026

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DEPARTMENT OF ELECTRICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Masters Thesis 2026

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Cover: Island Operation with Wind Turbines and Batteries (PSCAD)
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Typeset in LaTeX
Gothenburg, Sweden 2026

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Abstract

With the development of low carbon energy systems, microgrids are widely used in remote areas, islands, and weak grid regions where power supply is not stable. Wind and solar energy are abundant in these areas. Combining them with energy storage helps achieve clean and near zero carbon power supply. Our thesis studies a 0.4 kV islanded microgrid with wind power, photovoltaic generation, and battery storage. The system is built and simulated in PSCAD. Three conditions are tested: power surplus, power balance, and power shortage, to study how the system handles power coordination. The storage unit uses V/F control to form the grid and maintain voltage and frequency. Wind and photovoltaic units use PQ control to regulate active and reactive power. Wind and solar provide the main power, while storage smooths fluctuations and keeps the system stable. The results show that the storage charges when there is excess power and discharges when power is not enough. This keeps supply and demand balanced. Voltage and frequency remain stable during the whole process, which shows the control strategy is effective and reliable.

The report is written in English.

Keywords: Island microgrid; Wind, solar, storage system; Battery energy storage; V/F control; PQ control; PSCAD; Power balance; Voltage and frequency stability

Acknowledgements

We would like to express my sincere gratitude to Professor Ola Carlson for his valuable guidance, support, and encouragement throughout the completion of this thesis. His insightful advice and patient assistance have been extremely helpful to our research and writing process. We are truly grateful for the time and effort he has devoted to guiding me.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
AC/DC	Alternating Current to Direct Current
DC	Direct Current
DC/AC	Direct Current to Alternating Current
DC/DC	Direct Current to Direct Current
dq	Direct–Quadrature Axis Reference Frame
IGBT	Insulated Gate Bipolar Transistor
LC	Inductor–Capacitor Filter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NECP	National Energy and Climate Plan
PI	Proportional–Integral Controller
PLL	Phase-Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PQ	Active and Reactive Power Control
PSCAD	Power Systems Computer Aided Design
PV	Photovoltaic
PWM	Pulse Width Modulation
SOC	State of Charge
SPWM	Sinusoidal Pulse Width Modulation
V/F	Voltage/Frequency Control

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1 Introduction

This chapter provides a brief overview of the island power grid system project background and the significance of the research.

1.1 Background

Against the backdrop of the global energy transition, Sweden's National Energy and Climate Plan (NECP) has set the targets of achieving 100% fossil-free electricity production by 2040 and reducing greenhouse gas emissions by 75% by 2040 [1]. A key focus of this strategy is the expansion of wind and solar power generation. In addition, according to data from Statistics Sweden on electricity supply and use from 2001 to 2024, Sweden's overall national power system is relatively strong [2]. However, power supply remains constrained in remote areas, off-grid regions, and weak-grid areas, which makes the study of island microgrids of practical significance.

The island wind-photovoltaic-battery microgrid system studied in this thesis consists of wind power and photovoltaic power as the main generation units. The wind turbine converts wind energy into electrical energy, while photovoltaic panels convert solar radiation into electrical energy. However, both sources are inherently intermittent, fluctuating, and uncertain, which means they cannot provide a stable power supply and their output is often difficult to match with load demand. As a result, higher requirements are imposed on power balance and stable operation of the power system. Under such conditions, an energy storage system is introduced to regulate situations of power surplus or power shortage. This thesis aims to verify that, through an appropriate control strategy, coordinated operation among wind power, photovoltaic generation, and energy storage can be achieved, thereby demonstrating the power coordination capability of the island microgrid, the regulating role of energy storage, and the overall stability of the system.

1.2 Research Objectives and Scope

This thesis uses PSCAD software to model and analyze an island 0.4KV microgrid system (energy storage, wind power, and photovoltaics). The main focus is on the response of the energy storage system to changes in wind and solar power contributions and load demand.

Three operating scenarios are set up: power generation exceeding system load, maintaining basic balance, and insufficient power generation. The total simulation time is 6 seconds. The study examines the synergistic characteristics of the power generation system and load, as well as changes in parameters such as bus voltage, system frequency, and power output. This thesis only considers the system's dynamic response capability and does not consider its long-term economic performance or energy issues under highly complex conditions.

In the island wind-solar-battery microgrid studied in this thesis, the system operates independently. It is not connected to a large power grid. Therefore,

it does not have strong inertia support from the main grid. The voltage and frequency are more sensitive to power changes.

When the output of wind power or solar power changes randomly, the power balance in the microgrid may be broken. When a large local load is suddenly connected or removed, the same problem may also happen. These changes can cause frequency fluctuation and voltage fluctuation. They usually happen in a short time. So the lower-level control system needs a fast response and good stability.

Traditional energy management systems, also called EMS, are often used for day-ahead scheduling and energy optimization in microgrids. However, EMS usually works on a minute-level or hour-level time scale. It is more suitable for long-term energy balance and economic operation. It is not fast enough for the short-time power disturbance studied in this paper.

Therefore, our thesis does not focus on upper-level EMS scheduling. Instead, it mainly studies lower-level control methods. These methods include V-f control and real-time power sharing. The aim is to study how they support the voltage and frequency when the load changes suddenly.

To test the dynamic control ability more directly, a sudden load change condition is used in the simulation. This condition can represent a short-time disturbance in an island microgrid. It also helps to observe the response speed of the control method. It helps to show the power sharing effect and the recovery process of the system.

It should be noted that our thesis mainly studies the dynamic response under normal power fluctuation. The case where wind power or solar power is much higher than the load demand is not studied in detail. In this case, the battery is already fully charged, and the SOC reaches 100

This situation is not only a lower-level transient control problem. It is more related to upper-level EMS control. Possible methods include limiting renewable power, cutting off some generation units, using dump loads, or making the inverter work in a reduced-power mode.

If battery full-charge protection, wind and solar curtailment, and nonlinear energy limits are all added in this study, the control system will become more complex. It will also make it harder to show the effect of the V-f control method clearly.

Therefore, our thesis simplifies this extreme energy surplus condition at the present stage. The main focus is the response of the basic control strategy to load disturbance and normal power fluctuation. The coordinated control of renewable power limitation, unit cutting, and load dumping under full battery condition can be studied further in future work.



Figure 1: Chalmers' Wind turbine

Figure 1 shows Chalmers' wind turbine on Björkö. The island setting inspired the island wind-PV-battery microgrid system studied in our thesis.

2 Wind Power (Modeling and Control of Direct-Drive Permanent Magnet Synchronous Wind Power Generation)

2.1 General Architecture of a Wind Power Generation System

This thesis describes a wind power generation system based on a Permanent Magnet Synchronous Generator (PMSG). The system mainly consists of the aerodynamic components of the wind turbine blades, a mechanical transmission system, a PMSG, and a back-to-back converter. In this study, the wind power generation unit does not operate as a grid-forming source; instead, it functions as a grid-following power source for an isolated microgrid. The basic principle of wind power generation is the conversion of wind energy into electrical energy. Wind energy drives the turbine blades to rotate, thereby converting kinetic energy into mechanical energy. Through the mechanical shaft system, this mechanical energy drives the permanent magnets mounted on the rotor of the PMSG to rotate and establish a stable magnetic field. As the stator windings cut through this magnetic field, an electromotive force is induced in accordance with Faraday's law of electromagnetic induction, thereby generating electrical power [3]. As shown in figure 2, the back-to-back converter first rectifies the AC power generated by the PMSG into DC power and then inverts it into stable and reliable AC power suitable for grid connection [4].

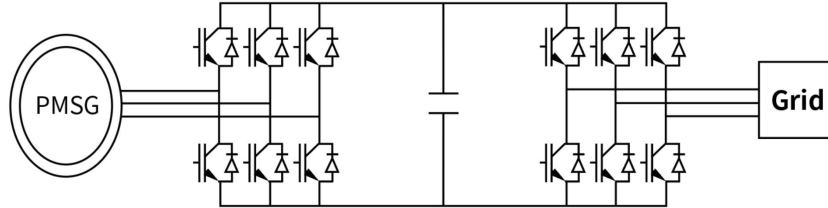


Figure 2: Configuration of the PMSG-based wind power generation system

2.2 Wind turbine aerodynamic model

Wind turbines convert wind energy into mechanical energy in wind power generation systems, and their ability to capture wind energy is crucial. Here are some core formulas [5]: The swept area of the wind turbine rotor can be expressed as

$$A = \pi R^2 \quad (2.2.1)$$

where R is the radius of the wind turbine rotor. The tip speed ratio can be expressed as

$$\lambda = \frac{\omega_m R}{v_m} \quad (2.2.2)$$

where ω_m is the mechanical angular velocity of the wind turbine, in rad/s, and v_m is the wind speed, in m/s. The mechanical power output of the wind turbine can be expressed as

$$P_w = \frac{1}{2} \rho \pi R^2 C_p v_w^3 \quad (2.2.3)$$

where ρ is the air density, in kg/m³, and C_p is the wind energy conversion coefficient of the wind turbine. The aerodynamic torque can be expressed as

$$T_m = \frac{P_w}{\omega_m} \quad (2.2.4)$$

Wind turbines capture wind energy through the rotor. Their aerodynamic characteristics are mainly described by the swept area, tip speed ratio, mechanical power, and mechanical torque, as expressed in (2.2.1)–(2.2.4).

The aerodynamic section mainly generates aerodynamic output power and outputs aerodynamic torque, laying the foundation for modeling the fan drive system and control system. Figure 3 shows the general wind turbine model in PSCAD.

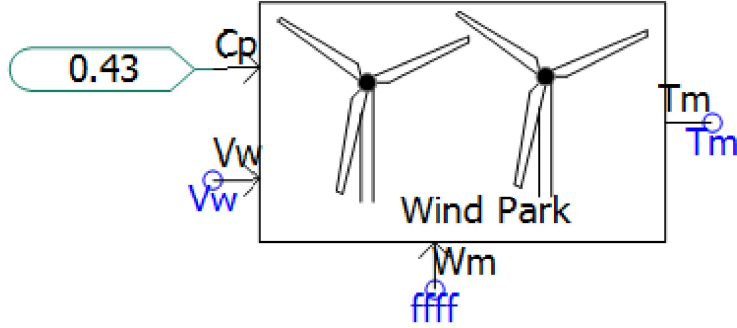


Figure 3: Aerodynamic Model of the Wind Park

Figure 4 illustrates the aerodynamic model adopted in this study. The radius of the wind turbine rotor is set to 40 m, the air density is 1.225 kg/m³, and the power coefficient is set to 0.43. The aerodynamic power P_w is then calculated and converted into the torque output T_m through ω_m .

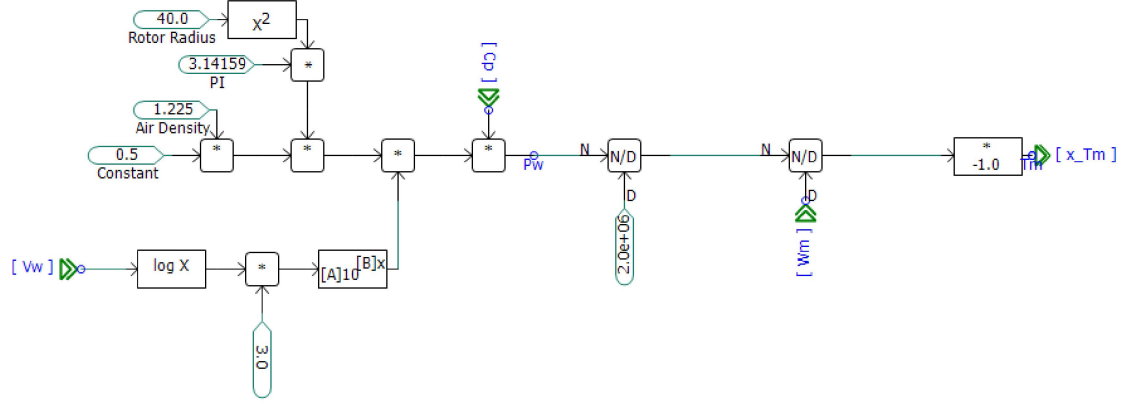


Figure 4: Aerodynamic power and mechanical torque calculation model of the wind turbine

In this thesis, the rated power of the wind turbine system is 125 kW. However, the simulation software does not provide ready-made startup parameters for a small-capacity wind turbine. Therefore, the parameters of a 2 MW wind turbine are used as the basic model. The aerodynamic part of the wind turbine is expressed in the per-unit system, so the variables are non-dimensional. After proper per-unit conversion and parameter scaling, the dynamic behavior of the 2 MW wind turbine can be used to represent the 125 kW wind turbine system. This method is acceptable for the modeling and simulation in this study.

2.3 Mechanical motion model

The mechanical transmission system mainly involves the relationship between the wind turbine output torque and the load torque [6]:

$$J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \quad (2.3.1)$$

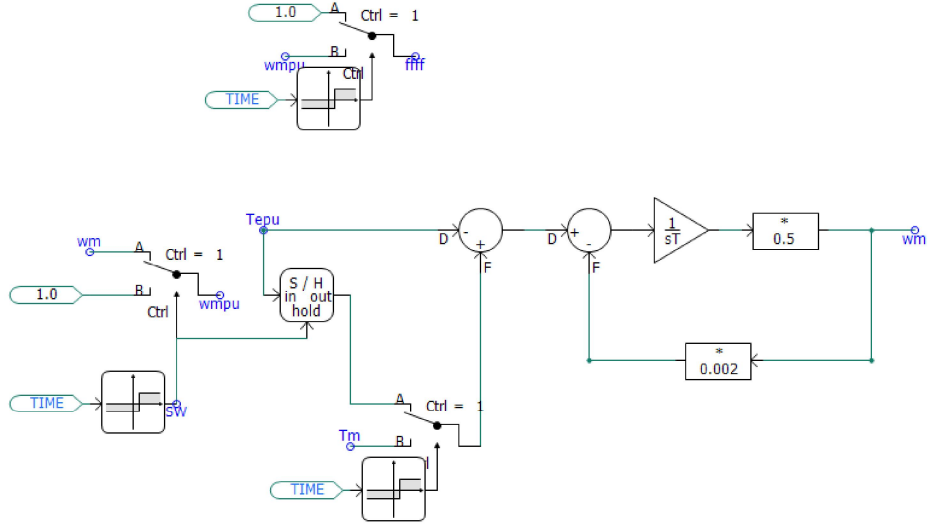


Figure 5: Mechanical transmission model in PSCAD

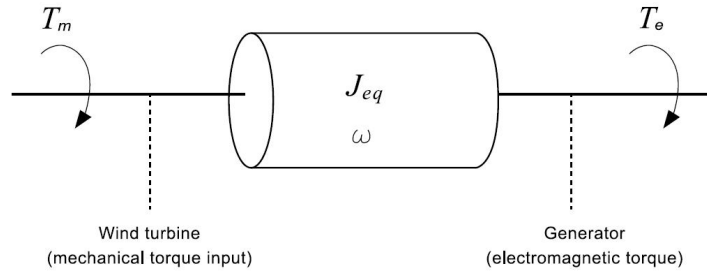


Figure 6: Mechanical transmission model

Figure 5 shows the transmission module of the model. On the left-hand side, the aerodynamic torque and the electromagnetic torque are taken as inputs. Through a summation block, the net input torque is obtained. In the dynamic link, the gain is set to 0.5 and the damping coefficient is 0.002. Figure 6 shows the equivalent mechanical transmission structure of the wind turbine-generator system.

2.4 Mathematical model of a PMSG (Permanent Magnet Synchronous Generator)

In this paper, the PMSG is chosen as the generator of the wind power unit because this generator is more suitable for island microgrids or weak grid conditions. The PMSG with a back-to-back converter realizes the electrical decoupling between the generator and the AC bus, and both the machine side and grid side can be controlled independently, so its dependence on the external grid is smaller. The grid side control adopts the grid voltage oriented vector control method [7], which ensures that the output power factor of the grid side is controllable. At the same time, the PMSG is more suitable for the direct-drive wind turbine used in this paper, because the PMSG performs better in outputting large torque at low speed [8]. In addition, the PMSG has built-in permanent magnets and does not need an extra excitation device, so it has a simple structure and high operating efficiency. Figure 7 shows the mathematical model of the PMSG used in PSCAD, where the mechanical speed and electromagnetic torque are the main variables of the generator model.

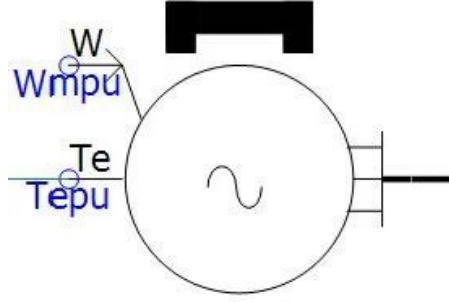


Figure 7: PMSG mathematical model

When modeling a PMSG, the dq model converts the symmetric three-phase AC components into DC components in the synchronous rotating reference frame, making the decoupling process and control method simpler. Before modeling, the following assumptions are made: 1. Ignore the internal eddy current and hysteresis losses of the generator; 2. The excitation magnetic field generated in the stator windings is sinusoidal, ignoring harmonics and saturation; 3. The electrical conductivity of the permanent magnet material is zero [9]. Align the d-axis with the fundamental wave direction of the rotor permanent magnet field, and the q-axis leads the d-axis by 90° . In the dq rotating reference frame, the PMSG is described by the flux linkage equations, voltage equations, and electromagnetic torque equation, as given in Eqs. (2.4.1)–(2.4.7).

Magnetic flux linkage equation:

$$\psi_d = \psi_f + L_d i_d \quad (2.4.1)$$

$$\psi_q = L_q i_q \quad (2.4.2)$$

Voltage equation:

$$U_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e \psi_q \quad (2.4.3)$$

$$U_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e \psi_d \quad (2.4.4)$$

Substitute the rotor flux linkage equation into the voltage equation. u_d and u_q are the d-axis and q-axis components of the generator stator voltage; R_s is the stator resistance; ω_e is the rotor electrical angular speed of the motor:

$$U_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (2.4.5)$$

$$U_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e \psi_f + \omega_e L_d i_d \quad (2.4.6)$$

Electromagnetic torque, where n_p is the number of pole pairs:

$$T_e = n_p [(L_d - L_q) i_d i_q + \psi_f i_q] \quad (2.4.7)$$

2.5 Motor side converter control method

For the turbine side control strategy of PMSG with direct-drive wind turbines, vector control methods generally include zero d-axis current control, unity power factor control, constant torque control, and MPPT control [10]. Since this paper focuses on the coordinated operation of wind, solar, and energy storage in an islanded grid, rather than the maximum wind energy capture of the turbines, this paper adopts constant speed control in the dq synchronous rotating coordinate system. This is more stable, easier to analyze, and facilitates the coordination between turbine side and grid-side control. The motor-side converter control is developed based on the PMSG electromagnetic torque equation, stator voltage equations, PI current controllers, and decoupling compensation terms, as given in Eqs. (2.5.1)–(2.5.8).

Specifically, the machine-side control in this paper adopts constant speed dual-closed-loop vector control, consisting of an outer speed loop and an inner current loop, with the current using the zero d-axis current method. From the synchronous rotating coordinate system dq, the electromagnetic torque equation of the motor is:

$$T_e = n_p [(L_d - L_q) i_d i_q + \psi_f i_q] \quad (2.5.1)$$

As can be seen from the formula, the electromagnetic torque mainly consists of permanent magnet torque and reluctance torque. If $i_d = 0$, the torque expression formula becomes simpler, so the torque is controlled by i_q . For a surface mounted-PMSG, $L_d \approx L_q$, and the reluctance torque is very small, so setting $i_d = 0$ has little impact on the simulation results. Finally, it reduces control coupling, allowing the motor side control to focus on i_q , making it simpler and clearer.

$$T_e = n_p \psi_f i_q \quad (2.5.2)$$

The PMSG stator voltage equation can be expressed as follows:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \quad (2.5.3)$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f \quad (2.5.4)$$

The d-axis and q-axis voltage equations contain the terms $-\omega_r L_q i_q$ and $\omega_r L_d i_d + \omega_r \psi_f$, respectively. To achieve independent adjustment of the d-axis and q-axis components, a feedforward decoupling compensation term is introduced.

$$u'_d = K_p(i_{dref} - i_d) + K_i \int (i_{dref} - i_d) dt \quad (2.5.5)$$

$$u'_q = K_p(i_{qref} - i_q) + K_i \int (i_{qref} - i_q) dt \quad (2.5.6)$$

The stator voltage command obtained is:

$$u_{dref} = u'_d - \omega_r L_q i_q \quad (2.5.7)$$

$$u_{qref} = u'_q + \omega_r L_d i_d + \omega_r \psi_f \quad (2.5.8)$$

The motor side control schematic diagram is shown below. In simple terms, the leftmost PI controller compares ω_{ref} with ω_r , and outputs i_{qref} after PI regulation. Therefore, the target of the outer loop control is the rotational speed. The inner loop is the current loop, in which i_q is compared with i_{qref} and regulated by a PI controller to obtain u'_q , while i_d is compared with i_{dref} and regulated by a PI controller to obtain u'_d . In the coordinate transformation, the three-phase i_{abc} is converted into i_d and i_q via Clark transformation, facilitating PI controller control. Finally, the controller outputs i_d and i_q are inverted into three-phase reference voltages $u_{a,ref}$, $u_{b,ref}$, and $u_{c,ref}$ via Park transformation, and then controlled by PWM modulation to achieve PMSG control.

Figure 8 shows the motor-side converter control structure, which adopts a dual closed-loop control scheme with an outer speed loop and inner dq-axis current loops.

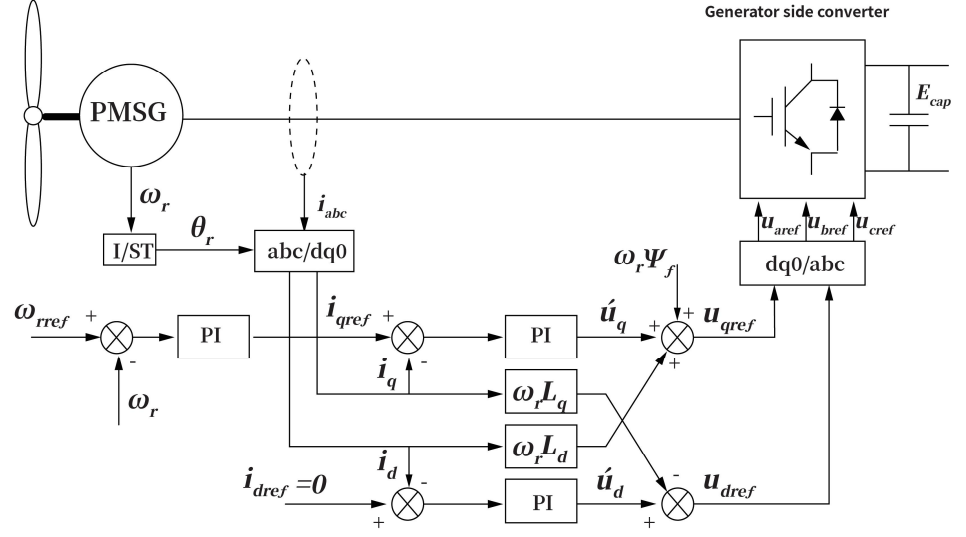


Figure 8: Motor side converter control

The PSCAD model is shown as follows. Figure 9 shows the signal input.

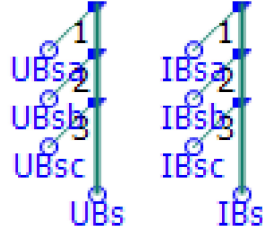


Figure 9: Signal input

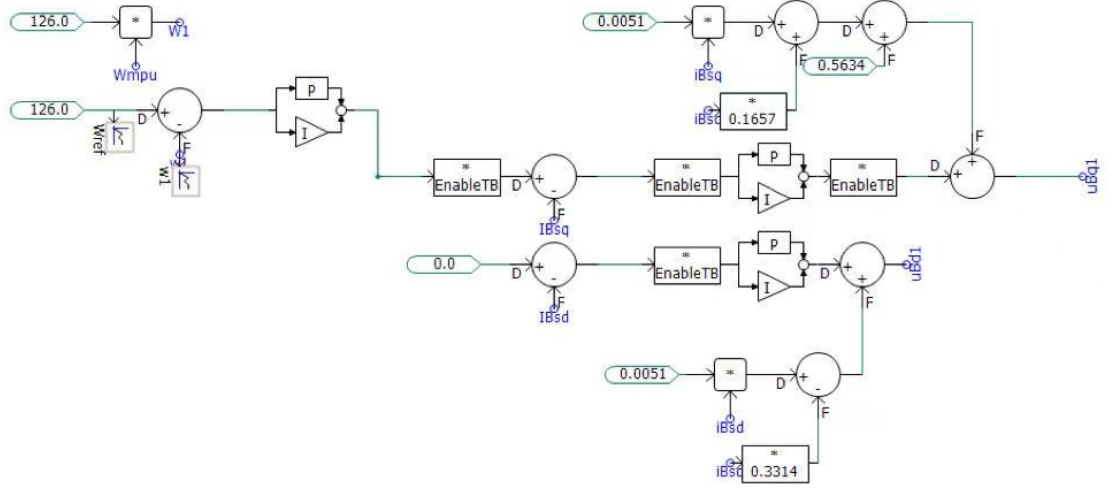


Figure 10: The outer speed control and inner current control

In Figure 10, the outer-loop ω_{ref} is the given speed value, which is 126 rad/s, and ω_m is the actual speed feedback value. These two values are used to check whether there is a speed error. If there is a speed error, the PI controller on the left generates a new current control value. In the inner current loop, the upper branch is the q-axis current, and the lower branch is the d-axis current. The d-axis current is 0 because zero d-axis current control is used. The PI controller on the right outputs the d-axis and q-axis voltages according to the current error between the reference current and the actual feedback current, together with the cross-coupling compensation terms. The other numerical terms in the figure are mainly used for decoupling calculation and proportional conversion. The PI controller parameters used in the control system are shown in Figure 11. Figure 12 presents the Clarke and Park transformations used for coordinate conversion, while Figures 13 shows the SPWM modulation circuit and the corresponding triangular carrier signal settings.

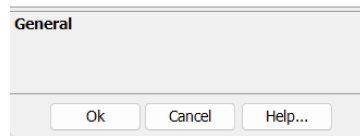
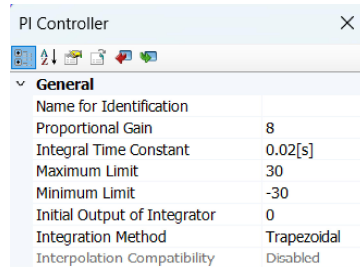


Figure 11: PI controller

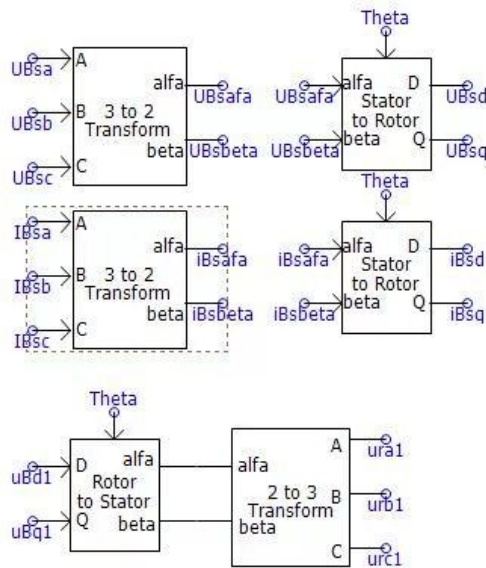


Figure 12: Clarke transformation and Park transformation

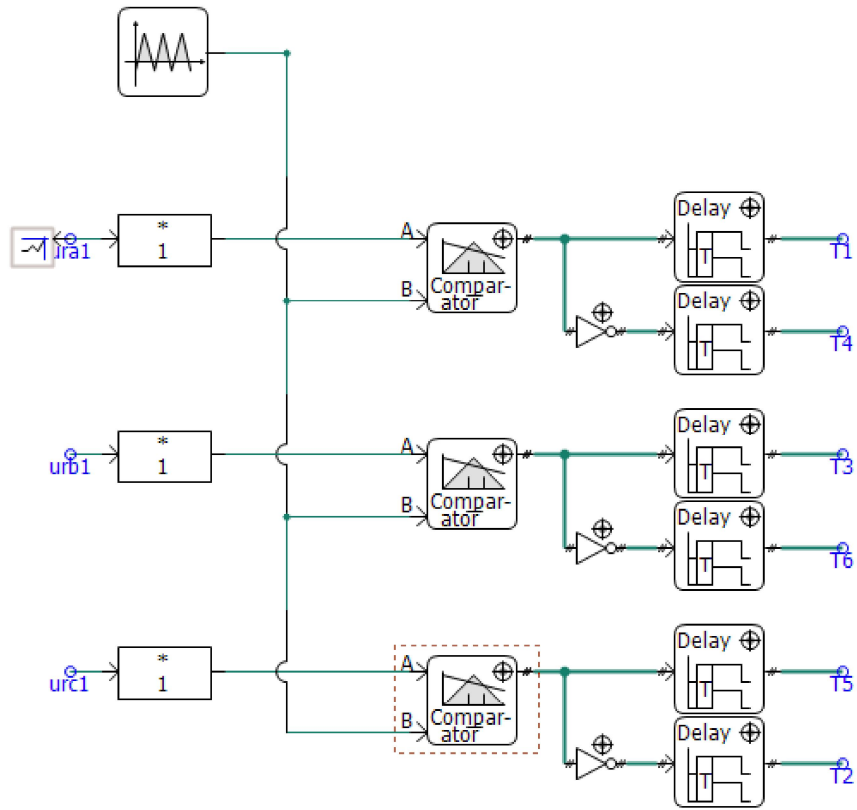


Figure 13: SPWM modulation

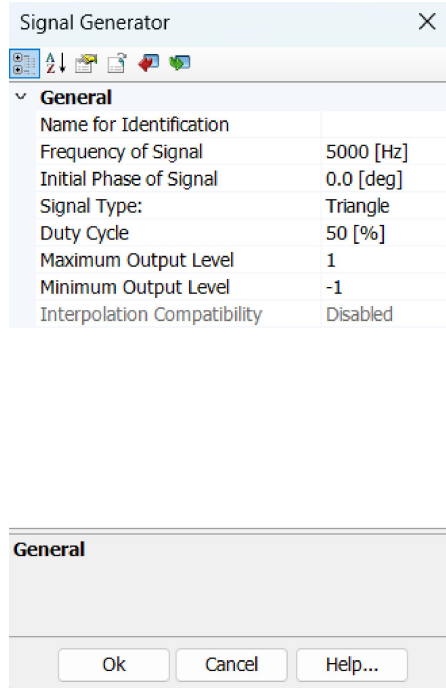


Figure 14: Parameter settings of the SPWM triangular carrier signal

Figure 14 shows parameter settings of the SPWM triangular carrier signal. Input the three-phase reference voltage signals and compare them with the high-frequency carrier signal in the comparator. When the reference signal is greater than the carrier, the output is 1. Otherwise, the output is 0, so pulse width modulation is realized. The lower switch trigger signal of each phase leg is inverted to get the upper switch trigger signal. The delay block is used to add dead time and prevent the upper and lower switches from turning on at the same time and causing a short circuit. Finally, six driving pulses are generated to drive the machine-side IGBTs.

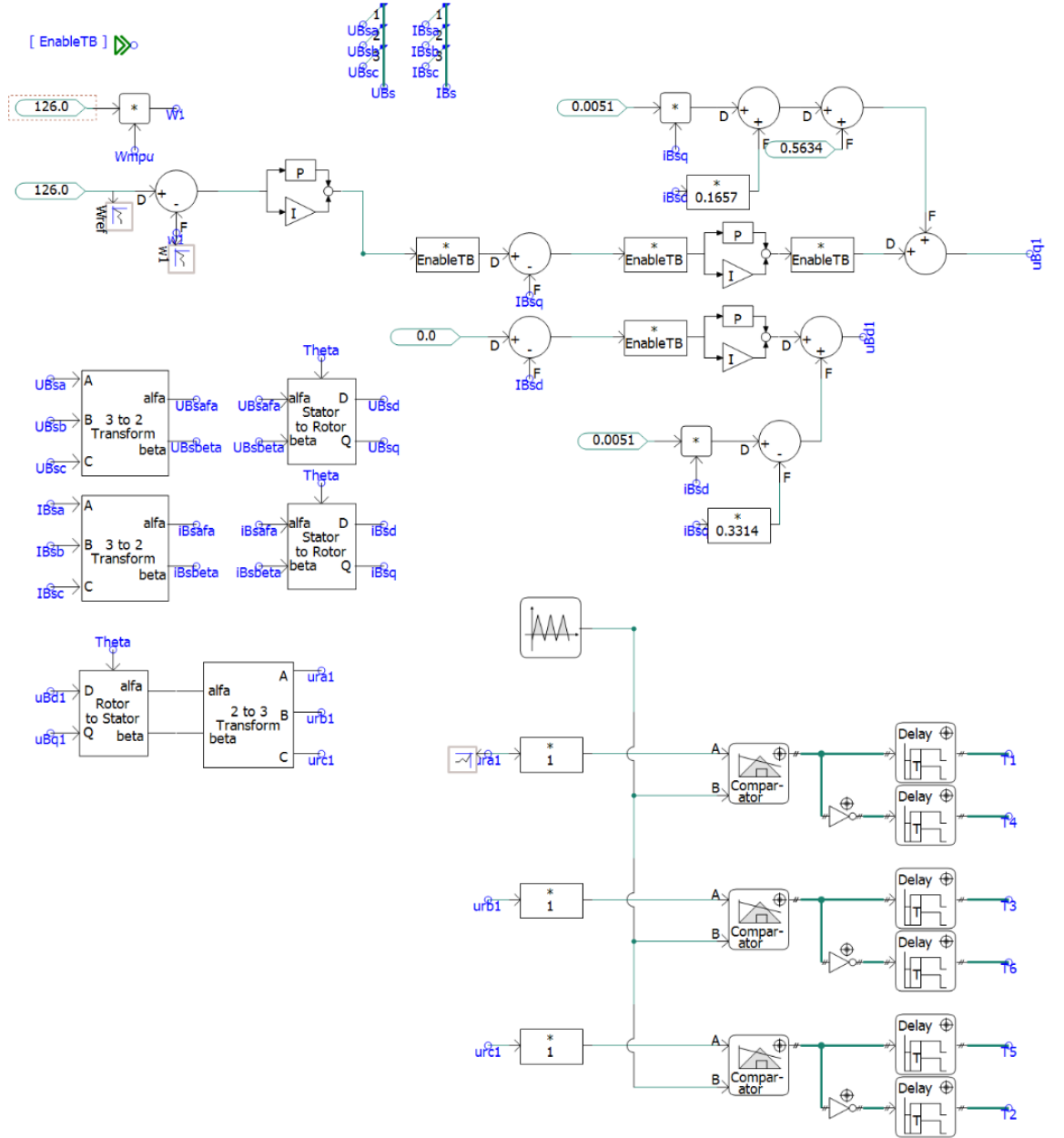


Figure 15: Wind power system

Figure 15 shows the Wind power system. The generator side adopts a double closed-loop control, including the speed outer loop and the current inner loop.

The error between the actual speed feedback value ω_m and the given speed ω_{ref} is sent to the outer-loop PI controller, which outputs the q-axis reference current i_q^* , while the d-axis reference current i_d^* is set to 0. Then, the actual d-axis and q-axis currents i_d and i_q are compared with the reference currents i_d^* and i_q^* , and the current errors are regulated by the inner-loop PI controllers to output the d-axis and q-axis voltage commands U_d^* and U_q^* . After that, U_d^* and U_q^* are converted into three-phase reference voltage signals through Park and Clarke transformations, and then they are sent to the SPWM module. Finally, six pulse signals are generated and applied to the machine-side IGBTs.

2.6 Grid-side converter control

The grid-side converter adopts constant DC voltage and constant reactive power control, which can stabilize the DC voltage, improve the power factor, and enhance stability. The grid-side control adopts a dual-loop control method based on the dq coordinate system. The phase-locked loop first obtains the voltage phase, transforming the three-phase voltage and current into the dq coordinate system. The d-axis controls the active power and DC bus voltage, while the q-axis controls the reactive power. The current error, after PI control, generates a voltage command, which, through feedforward compensation and decoupling, improves dynamic performance. The control signals, after inverse coordinate transformation and PWM modulation, maintain the stable operation of the system. The topology of the grid-side inverter is shown in Figure 16, including the three-phase filter, switching bridge, and DC-link capacitor. Eqs. (2.6.1)–(2.6.8) describe the dq-axis mathematical model and control strategy of the grid-side converter.

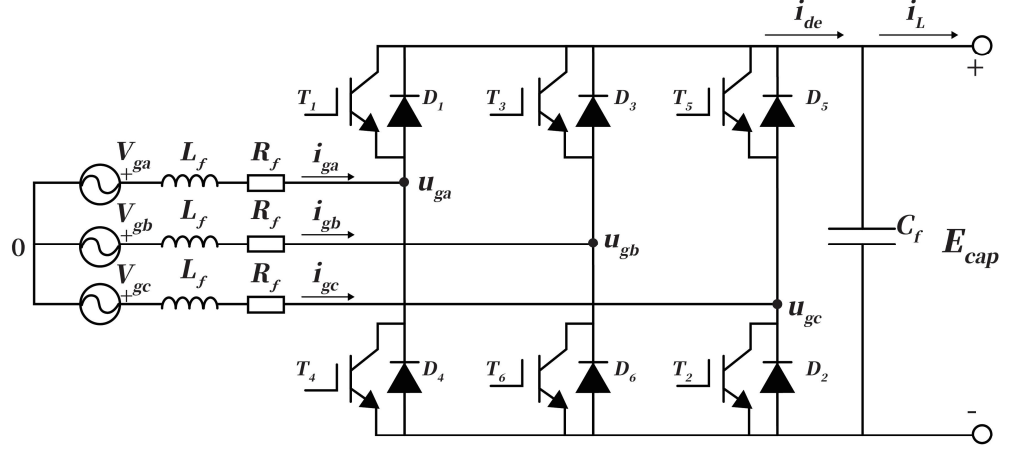


Figure 16: Grid-side inverter topology

Mathematical model in the dq coordinate system [11]:

$$\begin{cases} u_{gd} = -L_f p i_{gd} - R_f i_{gd} + \omega L_f i_{gq} + v_{gd} \\ u_{gq} = -L_f p i_{gq} - R_f i_{gq} - \omega L_f i_{gd} + v_{gq} \end{cases} \quad (2.6.1)$$

where u_{gd} and u_{gq} are the dq components of the inverter bridge arm output voltage; v_{gd} and v_{gq} are the dq components of voltage; i_{gd} and i_{gq} are the dq components of current; L_f and R_f are the filtering inductance and resistance, respectively; and p is the differential operator. Active and reactive power expressions:

$$\begin{cases} P_g = v_{gd} i_{gd} + v_{gq} i_{gq} \\ Q_g = v_{gq} i_{gd} - v_{gd} i_{gq} \end{cases} \quad (2.6.2)$$

Voltage is oriented along the d-axis:

$$\begin{cases} v_{gq} = 0 \\ v_{gd} = V_g \end{cases} \quad (2.6.3)$$

From the above, we can conclude that:

$$\begin{cases} P_g = V_g i_{gd} \\ Q_g = -V_g i_{gq} \end{cases} \quad (2.6.4)$$

Assuming two parameters u'_{gd} and u'_{gq} :

$$\begin{cases} u'_{gd} = L_f p i_{gd} + R_f i_{gd} = (L_f p + R_f) i_{gd} \\ u'_{gq} = L_f p i_{gq} + R_f i_{gq} = (L_f p + R_f) i_{gq} \end{cases} \quad (2.6.5)$$

It employs closed-loop current control within the inner loop and tracks the current through PI regulation:

$$\begin{cases} u'_{gd} = K_p(i_{gdref} - i_{gd}) + K_i \int (i_{gdref} - i_{gd}) dt \\ u'_{gq} = K_p(i_{gqref} - i_{gq}) + K_i \int (i_{gqref} - i_{gq}) dt \end{cases} \quad (2.6.6)$$

The grid-side inverter adopts unity power factor control, that is,

$$i_{gqref} = 0 \quad (2.6.7)$$

At the same time, add feedforward voltage compensation to achieve complete decoupling:

$$\begin{cases} u_{gdref} = -u'_{gd} + \omega L_f i_{gq} + V_g \\ u_{gqref} = -u'_{gq} - \omega L_f i_{gd} \end{cases} \quad (2.6.8)$$

Figure 17 shows the control diagram of the grid-side converter. The control strategy is a dual closed-loop control, with the outer loop being voltage control and the inner loop being current control. As shown in figure 17. Voltage and current are converted into current components in the dq coordinate system using a PLL (phase-locked loop). The outer loop controls the DC voltage, and the inner loop controls the reactive current. Then, PI control is applied to the voltage and current to ensure system stability.

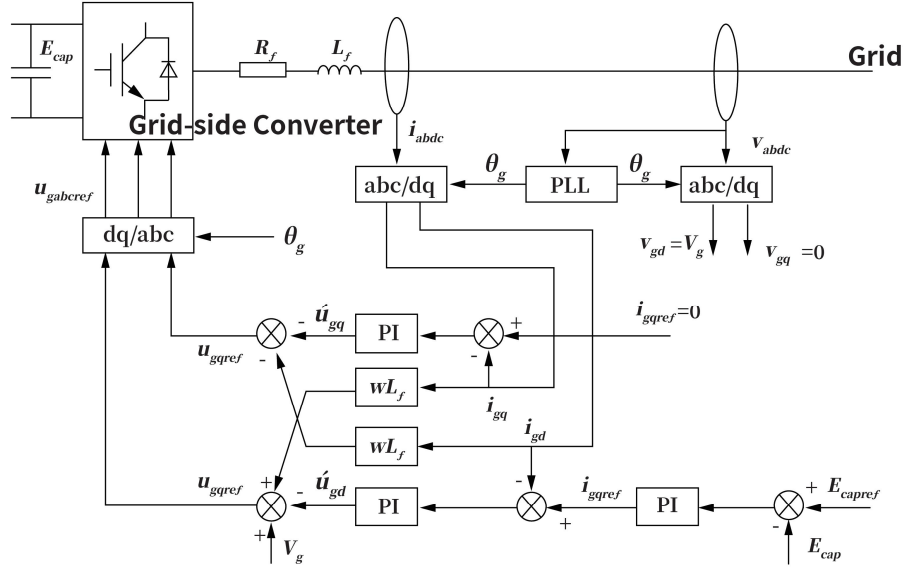


Figure 17: Control Diagram of the Grid-Side Converter

The module in figure 18 analyzes the three-phase voltage signals to obtain phase information, ensuring that the grid-side converter is synchronized with the power grid. $K_i = 900.0$, $K_p = 50.0$, and $V = 1.0$ V. The upper and lower tracking limits are 1.2 and 0.8, respectively.

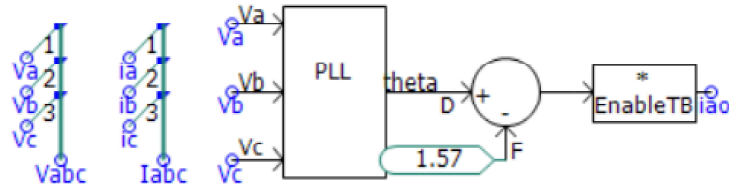


Figure 18: PLL module

Figure 19 is the 3-phase to 2-phase transformation. It converts the three-phase voltage to voltage in the dq coordinate system.

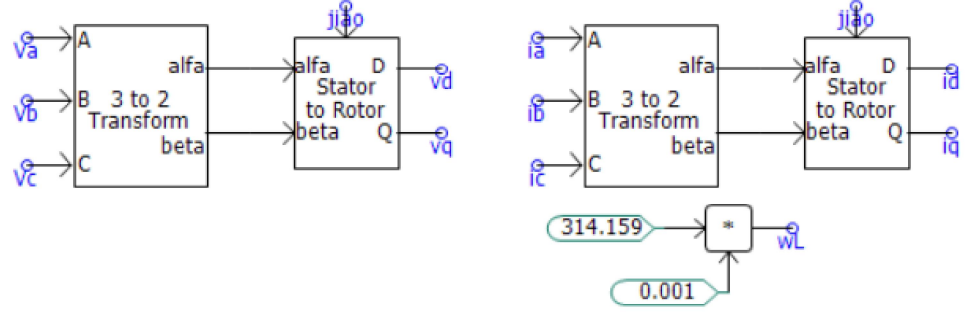


Figure 19: 3-phase to 2-phase transformation

Figure 20 is the current and voltage control module. It ensures that the output current and voltage follow the reference values, and achieve reactive power regulation. A control structure based on a PI regulator is used to generate the reference voltage and calculate the voltage command. The controller consists of a two-level closed-loop regulation scheme. In the first level, the given signal is compared with the feedback quantity, and the resulting error signal is processed to generate the reference current i_{dref} . In the second level, the actual current i_d is subtracted from the reference current i_{dref} , and the resulting error is processed by another PI regulator. Combined with the feedforward and compensation terms, this generates the voltage reference command V_{dref} .

Both PI regulators are configured with output saturation limits, where the maximum output is 20 and the minimum output is -20 . The proportional gain is set to $K_p = 5$, and the integral time constant is $T_i = 0.01$ s. Figure 21 is the whole system.

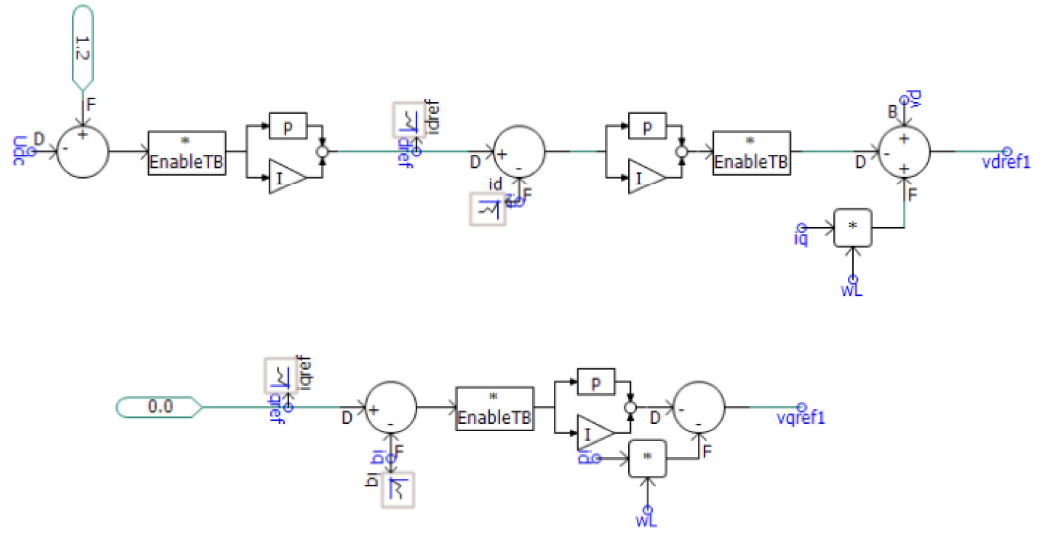


Figure 20: Current and voltage control module

Figure 21 shows the overall grid-side System.

3 Solar Power

This section mainly focuses on the photovoltaic power generation system, in which the PV array is connected to a boost converter and an inverter. After LC filtering and voltage boosting, the system can deliver grid-connected power at 50 Hz and 0.4 kV. Under rated operating conditions, with solar irradiance of 1000 W/m^2 and ambient temperature at or below 25°C , the photovoltaic system can output approximately 125 kW of power. This chapter provides a detailed introduction to the photovoltaic power generation part.

3.1 The principle of solar power generation

Silicon is a common insulator material. Its electrical conductivity is between that of a conductor and a semiconductor. At room temperature, it can generate a small number of free electrons and holes. After its electrical properties are adjusted by doping, its conductivity can also be obviously regulated, so it is especially suitable for making solar cells. Solar cells are the smallest units that make up photovoltaic modules. The more common ones are monocrystalline silicon solar cells and polycrystalline silicon solar cells. This paper will mainly introduce monocrystalline silicon solar cells. A monocrystalline silicon solar cell is formed by constructing a p-n junction inside a silicon wafer. From the outside, both p-type and n-type are electrically neutral, but the electron concentration in the n-type region is high and the hole concentration is low, while the hole concentration in the p-type region is high and the electron concentration is low. When the n-type region and the p-type region come into contact with each other, diffusion motion forms a space-charge region. In this region, a built-in electric field directed from n to p is formed. This is the p-n junction [12]. Figure 22 and Figure 23 shows the formation of the space charge region in the p-n junction

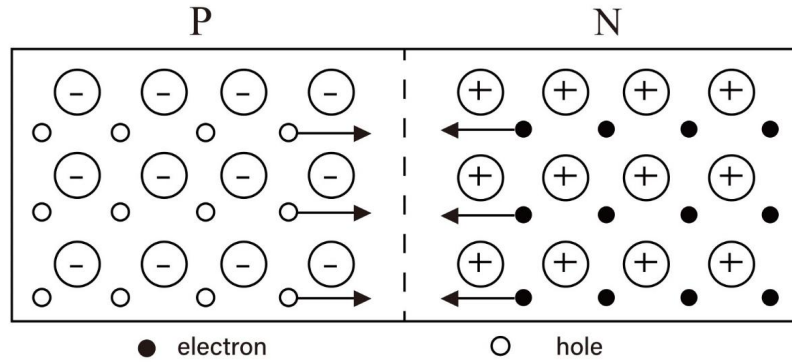


Figure 22: Diffusion movement

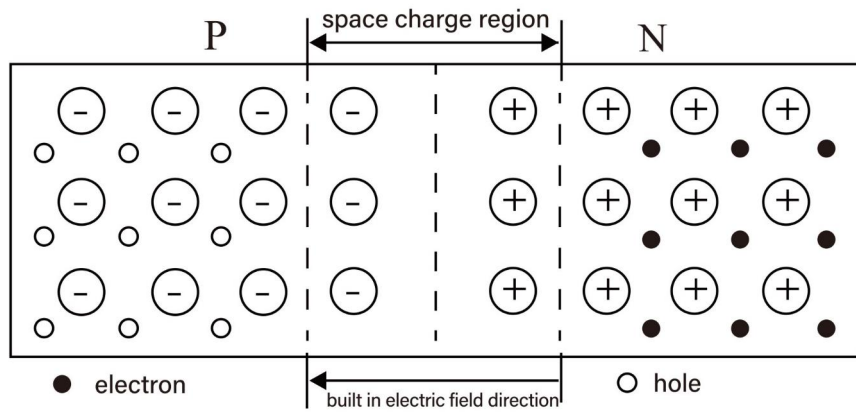


Figure 23: Formation of space charge region

When there is no light, there is a dynamic equilibrium inside the p-n junction. Holes in the p region diffuse to the n region, and electrons in the n region diffuse to the p region to form a built-in electric field, and the built-in electric field in turn prevents the diffusion motion. Under illumination, when the energy of the photon reaches a certain value, the electrons in silicon will break away from the bondage and generate electron-hole pairs. The electrons are pushed to the p region and the holes are pushed to the n region. There will be a voltage drop

at the two ends of the p-n junction and a voltage is generated. This is the photovoltage. Then, when a load and wires are connected outside, the electrons flow out from the n pole to the p pole, and the external circuit thus has current and can drive the load [11]. Figure 24 illustrates the solar cell power generation process under illumination.

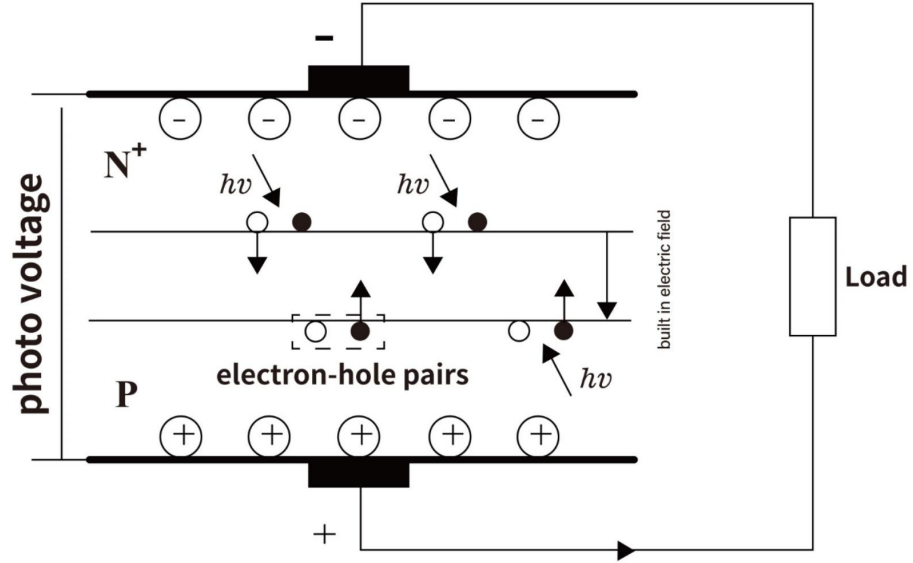


Figure 24: Schematic diagram of solar cell power generation principle

3.2 Mathematical model of the photovoltaic array

Photovoltaic cells are the most basic units in a photovoltaic power generation system. A single cell outputs very low voltage and current, and the power is also very small. A photovoltaic cell is essentially a large-area planar diode, and its working principle can be described using a single-diode equivalent circuit. Figure 25 shows a component that can be used to simulate a photovoltaic (PV) power source. Assume that the PV power source consists of several strings of PV modules connected in parallel, with each string possibly composed of several PV modules connected in series. It is assumed that all PV modules in the array are identical. The photo current, I_g , generated when the cell is exposed to light, varies linearly with solar irradiance. The current I_d through the anti-parallel diode is largely responsible for producing the nonlinear I-V characteristics of the PV cell [13].

Application of Kirchhoff's current law to the circuit gives:

$$I = I_g - I_d - I_{sh} \quad (3.2.1)$$

Substitution of relevant expressions for the diode current I_d and the shunt branch current I_{sh} yields:

$$I = I_g - I_0 \left[\exp \left(\frac{q(V + IR_{sr})}{nkT_c} \right) - 1 \right] - \frac{V + IR_{sr}}{R_{sh}} \quad (3.2.2)$$

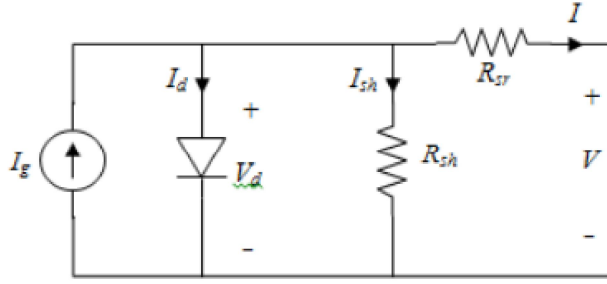


Figure 25: Solar Photovoltaic Cell Model

Figure 25 shows the equivalent circuit model of a solar photovoltaic cell, including the photocurrent source, diode, series resistance, and shunt resistance. Based on the equivalent circuit in Figure 25, the output current and voltage characteristics of the photovoltaic cell are described by Eqs. (3.2.1)–(3.2.4). Where V is the output voltage of the photovoltaic cell, I is the output current of the photovoltaic cell, I_g is the photocurrent source current, I_0 denotes the diode reverse saturation current, q is the elementary charge constant with a value of 1.602×10^{-19} C, k is the Boltzmann constant with a value of 1.381×10^{-23} J/K, T_c is the absolute operating temperature of the photovoltaic cell, and n is the diode characteristic fitting coefficient, which is a variable in the single-diode model.

Since, under normal conditions, R_{sh} is very large and R_s is very small. In an ideal situation, they can be ignored. Therefore, the ideal photovoltaic output current I can be expressed as:

$$I = I_g - I_d \left(e^{\frac{qV}{nkT_c}} - 1 \right) \quad (3.2.3)$$

The output voltage of the photovoltaic cell is:

$$V = \frac{nkT_c}{q} \ln \left(\frac{I_g - I}{I_d} + 1 \right) \quad (3.2.4)$$

Figure 26 shows some parameters of the photovoltaic source:

General	
Effective Area per Cell	0.036
Series Resistance per Cell	0.028
Shunt Resistance per Cell	1000
Diode Ideality Factor	1.5
Band Gap Energy	1.106
Saturation Current at Reference Conditions per Cell	1e-9 [A]
Short circuit Current at Reference Conditions per Cell	1.5 [A]
Temperature Coefficient of Photo Current	0.0017

(a) PV cell parameters

General	
PV Array Name	PVarray1
Number of Modules Connected in Series per Array	53
Number of Module Strings in Parallel per Array	11
Number of Cells Connected in Series per Module	12
Number of Cell Strings in Parallel per Module	20
Reference Irradiation	1000
Reference Cell Temperature	25
Graphics Display	industry

(b) PV array parameters

Figure 26: PV cell and PV array parameters

Figure 27 shows the current and power output characteristic curves of the photovoltaic cell. The solid line is the I-U curve, and the dashed line is the P-U curve. When the voltage increases, the photovoltaic output current remains basically stable in the early stage, and the output power first increases and then decreases with the voltage, reaching its peak at the MPP, which is the optimal operating point of the photovoltaic.

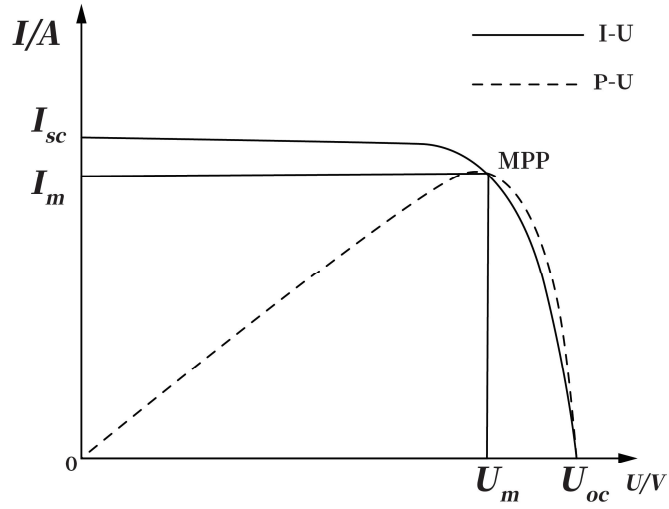


Figure 27: Photovoltaic Cell Current and Power Output Characteristic Curve

Figure 28 shows the V-I curves and P-V curves of the photovoltaic array under different sunlight intensities and PV module temperatures. The green curve in the middle represents the curve at 25 °C with an irradiance of 1000 W/m², operating approximately near the maximum power point [14]. We also use these parameters when we model.

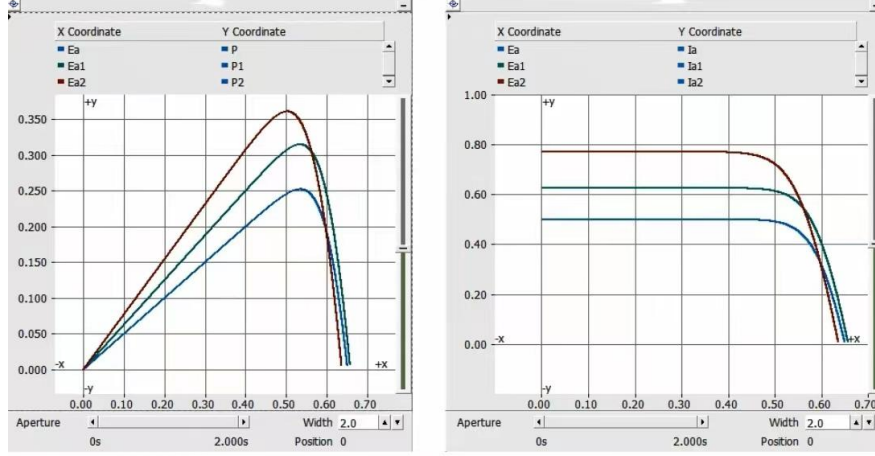


Figure 28: Photovoltaic characteristic curve

3.3 Photovoltaic system MPPT algorithm

In PSCAD, MPPT algorithms are divided into two types: one is the Perturb and Observe method, and the other is the Incremental Conductance method. The advantage of the Perturb and Observe method is that its principle is simple. Generally, measuring the current and voltage is enough, its cost is relatively low, and it is widely used. The advantage of the Incremental Conductance method is that the judgment of the maximum power point is clearer, and it is not easy to make wrong judgments when the illumination changes [15]. Because the simulation in this paper is only six seconds, it is assumed that the illumination is constant, so the Perturb and Observe method is adopted in this thesis. In addition, the efficiency deviation between the Perturb and Observe method and the Incremental Conductance method is very small, about 0.13% under dynamic conditions and about 0.02% under static conditions [16].

3.3.1 Perturb and Observe method

The P-U curve of a photovoltaic panel does not keep increasing all the time, but is like a parabola. On the left side of the highest point, the MPP point, the power increases with the increase of voltage, while on the right side of the MPP, the power decreases with the increase of voltage. When the photovoltaic cell operates on the left side of the maximum power point, the voltage needs to be increased to reach the MPP point; otherwise, the voltage needs to be reduced to reach the MPP point. The problem is that the system does not know whether it is operating on the left side or the right side at the beginning, so it can only try. The so-called perturbation in the perturb and Observe method is to add or subtract a small perturbation amount to the current operating voltage and observe the change in the output power of the photovoltaic cell [17].

Figure 29 shows the typical I-V and P-V characteristic curves of a PV array, where the maximum power point is located at the corresponding voltage V_{MPP} .

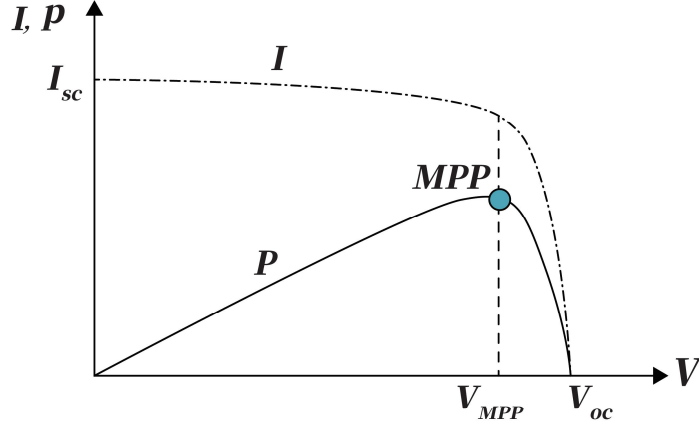


Figure 29: Typical I-V and P-V characteristics of a PV array

The specific working principle can be referred to from the flowchart. After the start, the voltage U_k and current I_k of the photovoltaic panel at the k sampling are sampled, and the current power $P_k = U_k I_k$ is calculated. Compared with the power P_{k-1} of the previous sampling, it is judged whether there is any change. If the power does not change, it means that it is basically close to the MPP point, and U_{ref} is returned directly without adjustment. If the power changes, then it is judged whether the power increases or decreases. An increase in power means that the perturbation direction is correct, and a decrease in power means that the perturbation direction is wrong. If the power increases, the voltage is adjusted further in the same direction. If the power decreases, the voltage is adjusted in the opposite direction [18]. There are four situations. In the first situation, the voltage increases and the power also increases, and at this time the voltage should continue to be increased. In the second situation, the voltage increases and the power decreases, and at this time the voltage should be reduced. In the third situation, the voltage decreases and the power increases, and at this time the voltage should continue to be reduced. In the fourth situation, the voltage decreases and the power also decreases, and at this time the voltage should be increased.

Figure 30 shows the flowchart of the Perturb and Observe method, where the reference voltage is adjusted according to the change in PV output power to

track the maximum power point.

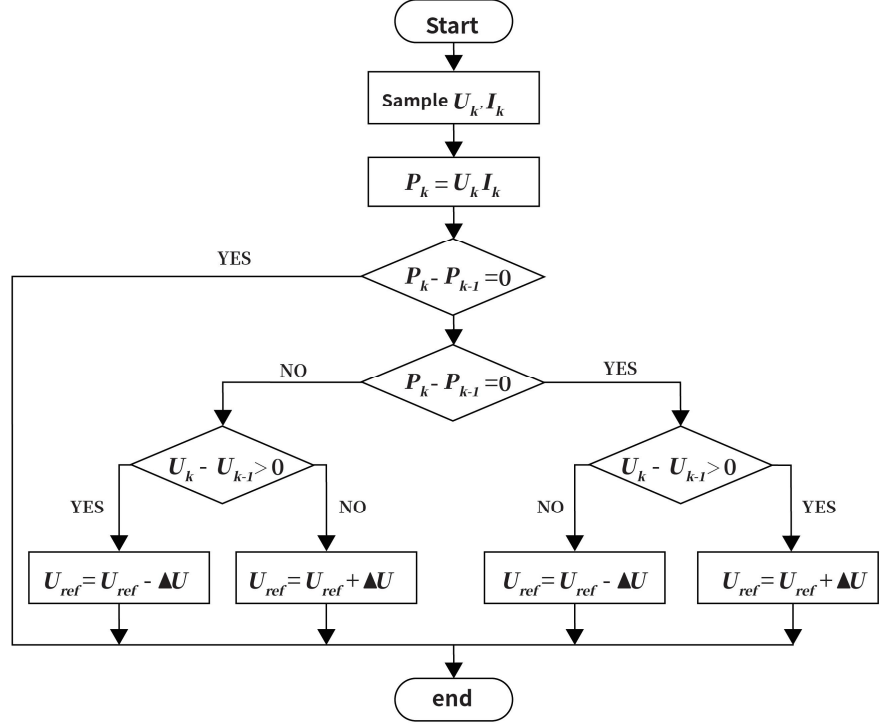


Figure 30: Flowchart of the Perturb and Observe Method

3.3.2 Incremental Conductance method

The principle of the Incremental Conductance method is derived from the condition that the power slope is zero at the maximum power point, as shown in Eqs. (3.3.2.1)–(3.3.2.9).

The photovoltaic panel also has a P-U curve, and the maximum power point is the highest point on this curve. At the highest point, there is a very important characteristic:

$$\frac{dP}{dU} = 0 \quad (3.3.2.1)$$

This means:

On the left side of the MPP, the power increases with the increase of voltage, so the slope is greater than 0. On the right side of the MPP, the power decreases with the increase of voltage, so the slope is less than 0. At the MPP point, the

slope is exactly equal to 0 [18]. Because:

$$P = UI \quad (3.3.2.2)$$

So, differentiating with respect to voltage U :

$$\frac{dP}{dU} = I + U \frac{dI}{dU} \quad (3.3.2.3)$$

At the maximum power point:

$$\frac{dP}{dU} = 0 \quad (3.3.2.4)$$

Therefore:

$$I + U \frac{dI}{dU} = 0 \quad (3.3.2.5)$$

Then

$$\frac{dI}{dU} = -\frac{I}{U} \quad (3.3.2.6)$$

$$\frac{dP}{dU} = 0 \quad (3.3.2.7)$$

Incremental conductance:

$$\frac{dI}{dU} \quad (3.3.2.8)$$

Instantaneous conductance:

$$-\frac{I}{U} \quad (3.3.2.9)$$

It follows that $\frac{dP}{dU} = I + U \frac{dI}{dU}$. When the operating point is at the maximum power point, we have $\frac{dI}{dU} = -\frac{I}{U}$. When $\frac{dI}{dU} > -\frac{I}{U}$, the operating point is on the left side of the maximum power point, and the operating voltage should be increased. When $\frac{dI}{dU} < -\frac{I}{U}$, the operating point is on the right side of the maximum power point, and the operating voltage should be decreased. This method determines the position of the operating point by comparing the incremental conductance with the instantaneous conductance, thereby achieving maximum power point tracking.

Figure 31 shows the flowchart of the Incremental Conductance MPPT method, where the reference voltage is adjusted by comparing the incremental conductance with the instantaneous conductance.

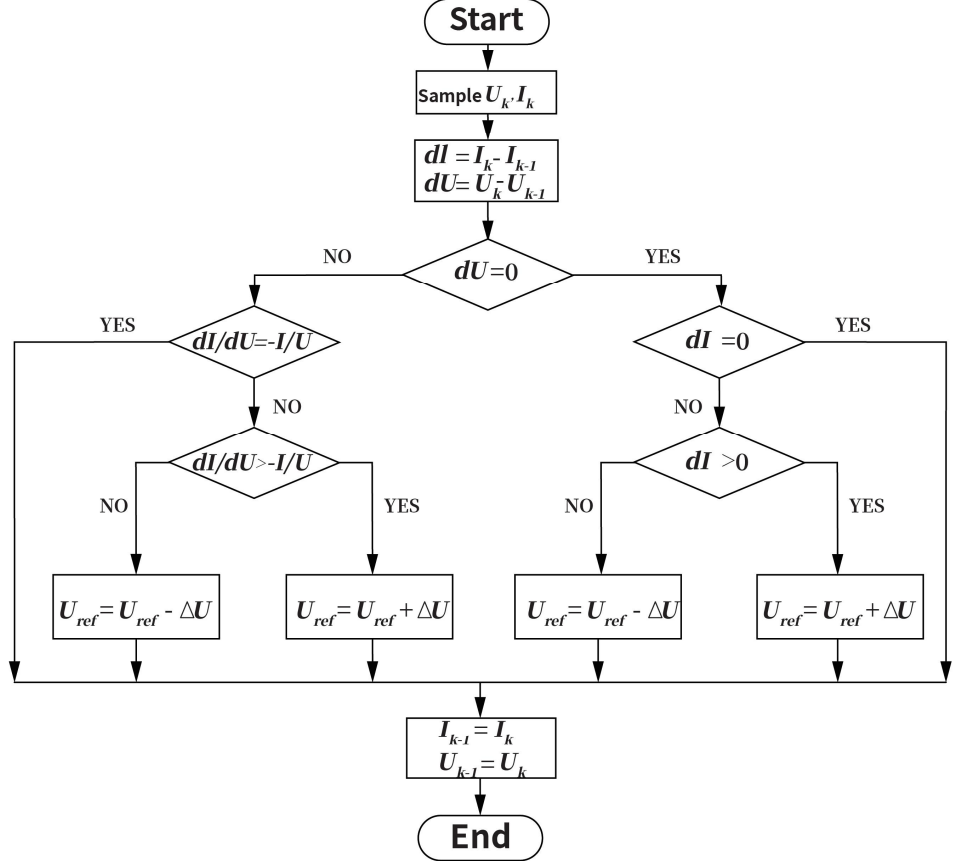


Figure 31: Flowchart of the Incremental Conductance Method

3.4 Photovoltaic Grid Connected Control Strategy for Power Generation Systems

Photovoltaic systems typically employ a power (PQ) control strategy when connected to the grid, including inner-loop current control and outer-loop power control. The three-phase AC electrical quantities (abc) are converted into DC quantities in the dq coordinate system, and the phase-locked loop tracks the grid frequency. After the dq transformation, the q-axis voltage component is 0, and the power can be expressed as:

$$\begin{cases} P = u_d i_d \\ Q = -u_d i_q \end{cases} \quad (3.4.1)$$

As shown in formula 3.4.1, active power is controlled by the d-axis current, and reactive power is controlled by the q-axis current. Using the d-axis and q-axis currents in 3.4.1 as reference current inputs, the output voltage undergoes inverse transformation to generate a sinusoidal modulated signal. This signal is then controlled by an SPWM three-phase inverter, and the resulting voltage signal is fed into the power grid, as shown in the Figure 32.

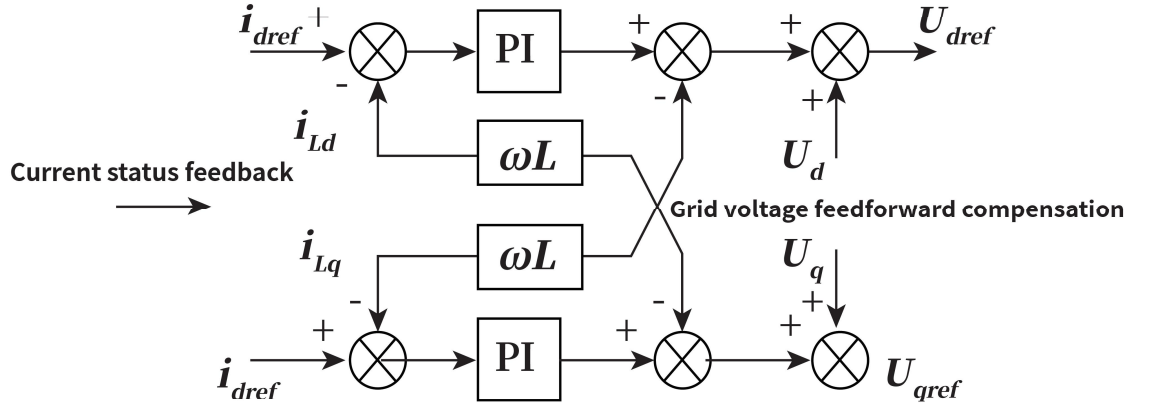


Figure 32: Current loop control principle

Figure 33 shows the structure of the PQ control strategy. First, the output voltage and current U_{pv} and I_{pv} are sampled, and the active power reference value P_{ref} is obtained through the MPPT algorithm. Single power factor grid-connected operation is used, so the reactive power reference value Q_{ref} is 0. Then, the reference currents for the d-axis and q-axis are calculated as the inner current loop input. Simultaneously, the grid-connected currents I_{abc} and U_{abc} are transformed by dq to obtain the actual values of the d-axis and q-axis currents. The current controller compares the reference value and the feedback value, and obtains the three-phase voltage reference signal through dq/abc inverse transformation, which is then used by the SPWM module to generate drive pulses.

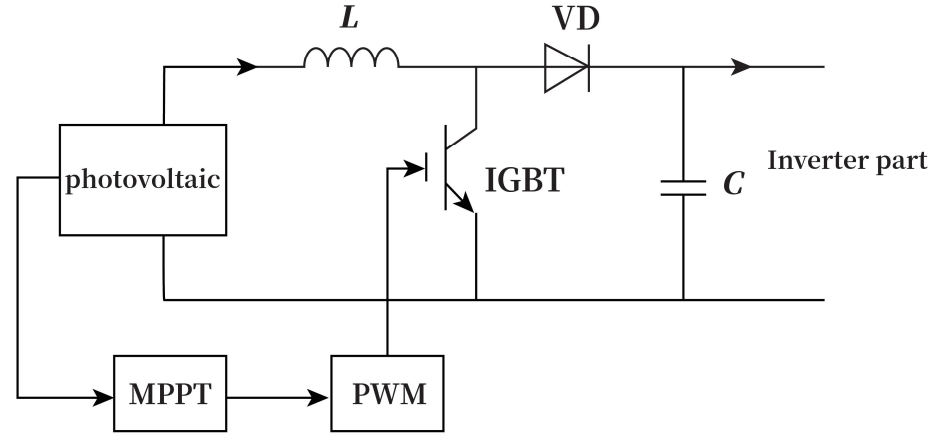


Figure 34: MPPT control structure

Figure 35 shows Photovoltaic system simulation in PSCAD. In the PSCAD simulation, the photovoltaic panel circuit consists of a photovoltaic array, a Boost circuit, a DC-link capacitor, a three-phase inverter, a filter circuit, and the grid-connection part. Figures 36–39 show the main PSCAD implementation blocks of the photovoltaic system, including the PV panel control component, the test circuit, the MPPT circuit, and the Boost control circuit.

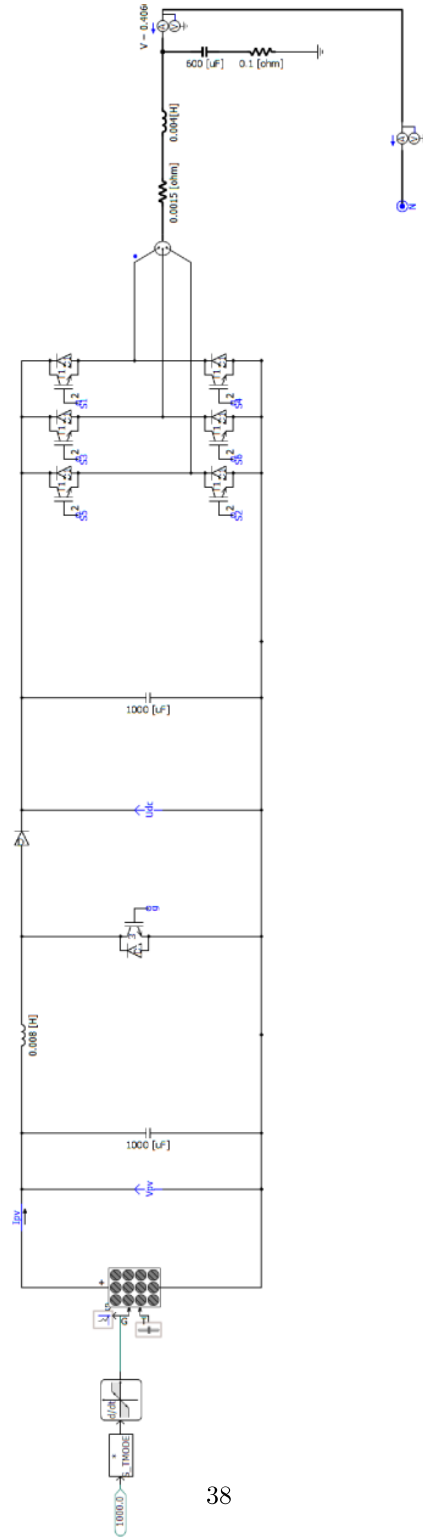


Figure 35: Photovoltaic system simulation in PSCAD

The settings of the photovoltaic panel control component are show in Figure 36 : the reference voltage is 0.4 kV, the temperature is 25 °C, and the MPPT function is enabled.

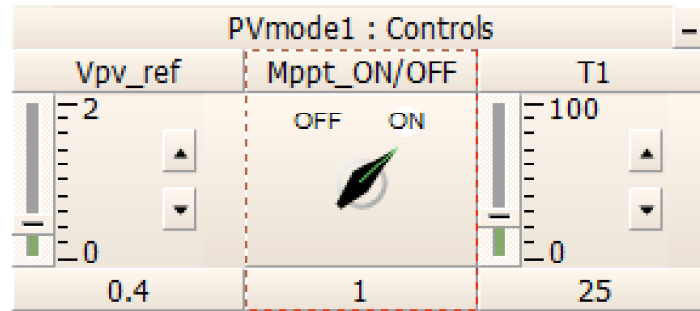


Figure 36: Photovoltaic panel control component

From the photovoltaic panel test circuit shown in Figure 37, the open circuit voltage of the photovoltaic panel is measured to be 508 V and the short circuit current is 352 A, which are entered into the MPPT module, and the MPPT module uses the Perturb and Observe method. To measure the open circuit voltage, a large resistor is connected in parallel, while to measure the short circuit current, a small non-zero resistor is connected in parallel.

Figure 39 shows boost control circuit. Boost control circuit is to ensure that the voltage at both terminals connected to the inverter operates at the voltage V_{mppt} corresponding to the maximum power output, and to ensure that the power delivered by the inverter is the maximum power of the photovoltaic system, the controller first compares V_{mppt} with V_{pv} to obtain the error, which is then sent to the PI controller. The PI controller outputs a modulation signal according to the error. The modulation signal is compared with the carrier to generate PWM, and the PWM controls the Boost switch to change the duty cycle and regulate the photovoltaic terminal voltage. Finally, V_{pv} can be stabilized near V_{mppt} .

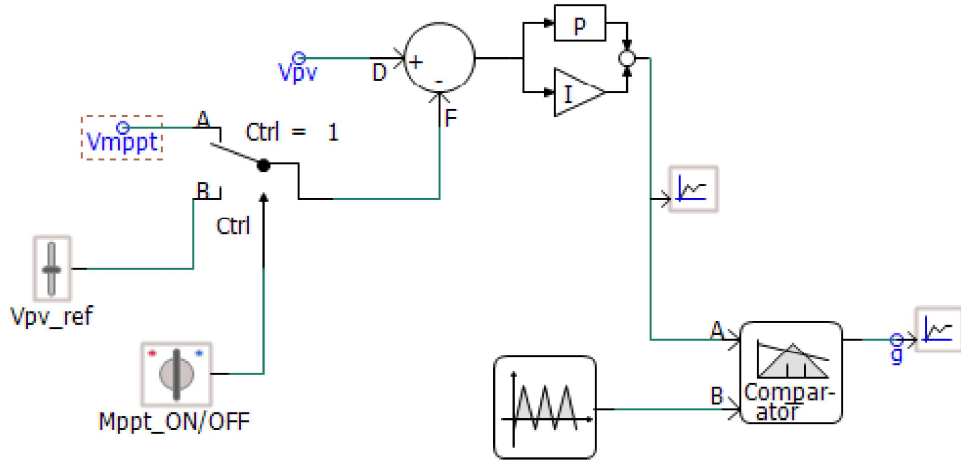
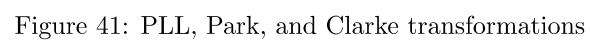


Figure 39: Boost control circuit

First, the three-phase voltage and current signals, V_{abc} and I_{abc} , are sampled. Then, the grid phase angle is obtained through the PLL. After that, the three-phase quantities are transformed into the d -axis and q -axis quantities through the Clarke transformation and the Park transformation. In the outer power loop, the PI controller generates the reference currents i_d^* and i_q^* . In the inner current loop, the reference voltages are compared with the actual voltages, and the PI controller outputs V_d^* and V_q^* . Then, the inverse Park transformation is carried out to obtain the triangular modulation waves, which are compared with the triangular carrier for SPWM pulse width modulation to generate six driving signals for the inverter switches. The delay block is used to prevent the IGBTs from being turned on or turned off simultaneously.

Figures 40–44 show the grid-connected inverter control blocks, including signal sampling, PLL and coordinate transformations, dual closed-loop control, inverse Park transformation, and SPWM modulation.



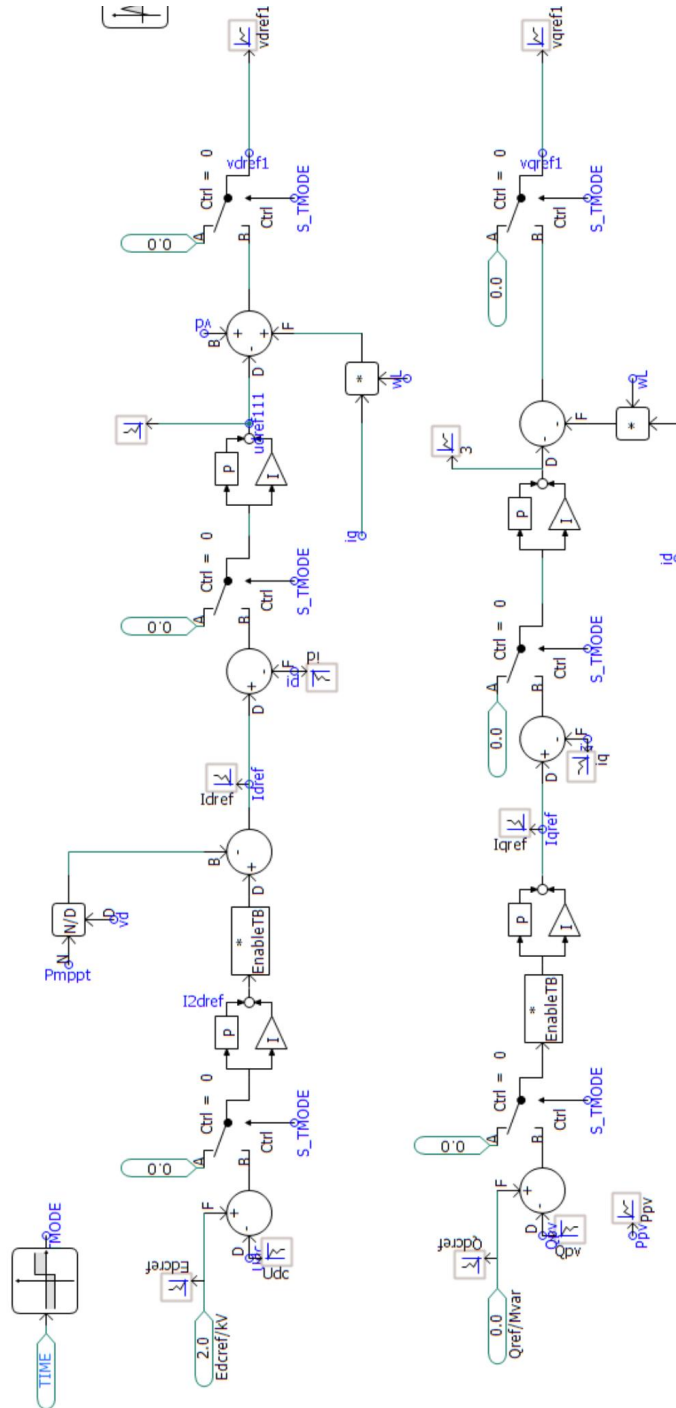


Figure 42: Dual closed-loop control

4 Energy Storage Module

This thesis employs a Shepherd type battery model combined with DC/DC and DC/AC to achieve charging and discharging between the battery and the power grid, and uses V/F control through an island system to support frequency and voltage.

4.1 Battery model

Rechargeable batteries are very important in power systems because they provide a way to store a small amount of energy. There are also many factors that affect the performance of different batteries. The battery model used in this article is based on the literature [19]. A controlled voltage source and series resistance are used to represent the battery. The battery terminal voltage is expressed by Eq. (4.1.1), where the effect of the internal resistance is considered in the equivalent battery model. Figure 45 shows the equivalent circuit of the battery, which consists of a controlled voltage source and an internal resistance.

$$V_{bat} = E_{bat} - I_{bat} \cdot R_{bat} \quad (4.1.1)$$

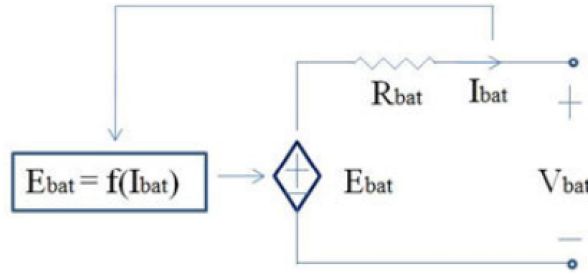


Figure 45: Battery Equivalent Circuit

Figure 46 shows the nonlinear battery model, and the controlled voltage source is simplified as a function of SOC, as given in Eq. (4.1.2). At each time step, the calculation of the controlled voltage source is based on a nonlinear equation, which uses the actual state of the battery to calculate the open-circuit voltage, assuming the resistance value is constant. Where E denotes the no-load voltage, E_0 is the battery constant voltage, K represents the polarization voltage, Q is the battery capacity, $\int i dt$ is the actual battery charge, A denotes the exponential zone amplitude, and B is the inverse of the exponential zone time constant.

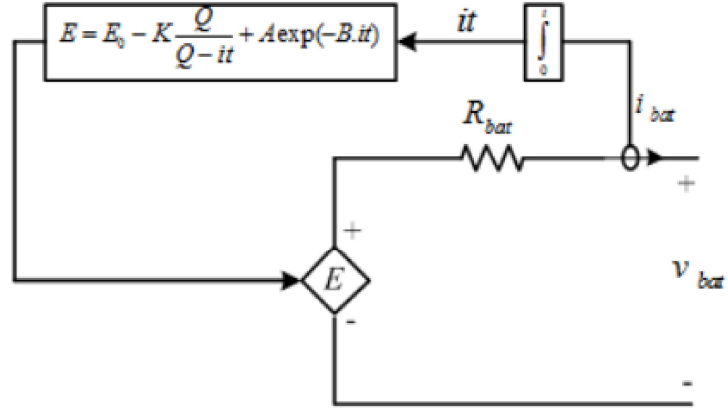


Figure 46: Non-Linear Battery Model

In order to simplify the equation using SOC, the equation is as follows:

$$E = E_0 - K \cdot \frac{1}{SOC} + A \cdot e^{-BQ(1-SOC)} \quad (4.1.2)$$

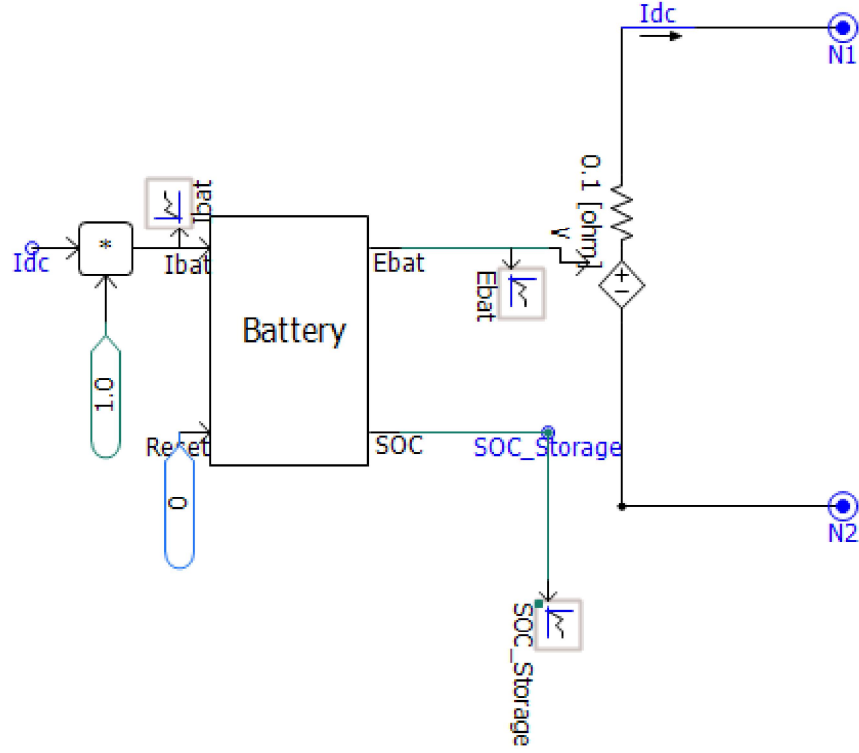


Figure 47: Battery Model in PSCAD

Figure 47 presents the battery model implemented in PSCAD, Figure 48 lists the main battery parameters used in the simulation. The input terminals are the current signal I_{bat} and the reset signal $Reset$. The current signal drives the state update, and the reset signal is used to reset the SOC integration process. The output terminals are the equivalent open-circuit voltage E_{bat} and the state of charge SOC storage. According to the battery parameters, the nominal pack voltage is 540 V. The actual terminal voltage varies with the state of charge and battery current. The battery parameters are shown in the figure:

reated capacity (Ah)	1 [Ah]
reserved battery (Ah)	0.8 [Ah]
nominal capacity (Ah)	0.85
Maximum voltage (V)	4.2 [V]
voltage at exponential point (V)	3.9 [V]
charge current (A)	0.5 [A]
effeciency	0.995
number of seriesed battery	150
number of paralleled battery	150
nominal voltage (V)	3.6 [V]

Figure 48: Battery parameters

4.2 DC/DC Converter

This thesis adopts a non-isolated bidirectional Buck-Boost half-bridge converter circuit as the circuit topology of the bidirectional DC/DC converter. The traditional Buck-Boost topology is shown in Figure 49.

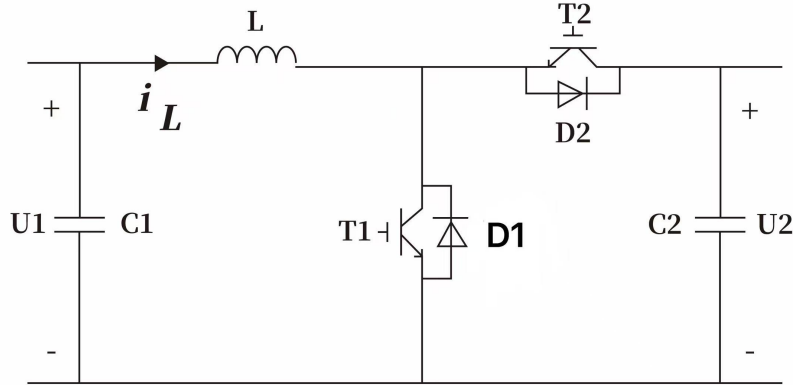


Figure 49: Buck-Boost circuit topology

The bidirectional Buck-Boost circuit evolved from the Buck and Boost circuits, and can operate in either Buck or Boost mode. The core principle is to control switches T_1 and T_2 to store energy in the inductor and then release that energy to the other side [20]. Figure 50 shows the Buck-Boost converter's workflow. In state (a), T_1 is turned on and T_2 is turned off. Due to the freewheeling effect

of D_1 , no current flows through T_1 . The inductor current i_L decreases in the reverse direction from $i_{L\min}$ to 0. During this process, the energy stored in the inductor is returned to the battery.

In state (b), T_1 is turned on and T_2 is turned off. Both D_1 and D_2 are reverse-biased. The inductor current i_L increases linearly, and the current flows through $U_1 - C_1 - L - T_1$. The battery discharges to the inductor.

In state (c), T_1 is turned off and T_2 is turned on. D_1 is reverse biased. Due to the freewheeling action of D_2 , no current flows through T_2 . The inductor current i_L decreases from $i_{L\max}$, and the current flows through $L - T_2(D_2) - U_2 - C_2$. The inductor transfers energy to the DC bus.

In state (d), T_1 is turned off and T_2 is turned on. Both D_1 and D_2 are reverse-biased. The current flows through $U_2 - T_2 - L - U_1$. The current direction is opposite to the defined positive direction of i_L . Since T_2 is conducting, D_2 is not conducting. The energy is transferred from U_2 to the inductor and battery U_1 , and the battery is charged.[21]

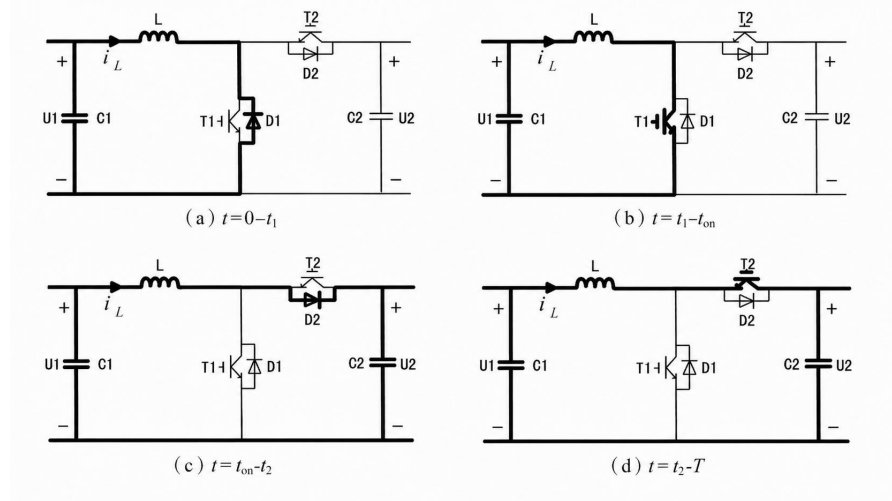


Figure 50: Buck-Boost workflow

The following Figure 51 shows a Buck-Boost circuit simulated in PSCAD. The left side is the low voltage side connected to the battery, denoted as U_2 , and the right side is the high voltage side connected to the DC side of the inverter, denoted as U_1 . The inductance in the figure is 2 mH, whose function is energy storage to realize the energy transfer of step up and step down. The 2 mF capacitor on the left side is used to stabilize the voltage of U_2 , and the 5 mF capacitor on the right side is used to stabilize the voltage of U_1 . First, when T_1 is turned on, the high voltage side supplies energy to the inductor, then when T_1 is turned off and T_2 provides freewheeling, the inductor releases energy, and at this time it operates in the Buck state for step down charging. First, when T_2 is

turned on, the low voltage side charges the inductor, then when T_2 is turned off and T_1 is turned on, the inductor releases energy, and at this time it operates in the Boost state for step up discharging.

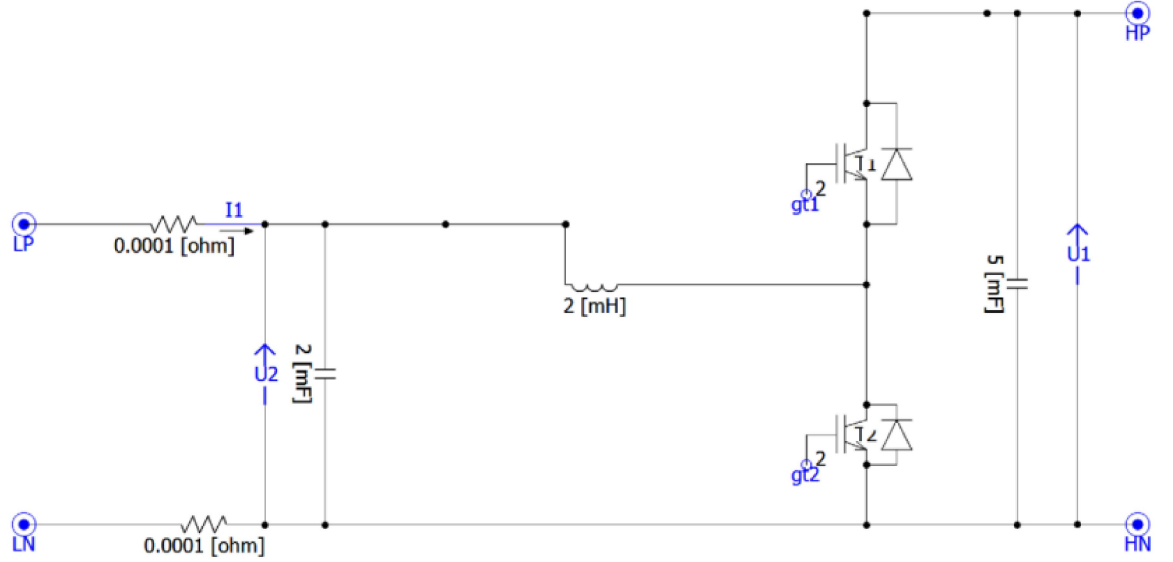


Figure 51: Buck-Boost simulation in PSCAD

The following Figure 52 shows the control circuit of the bidirectional Buck-Boost converter, which realizes bidirectional power flow through a voltage outer loop + current inner loop + PWM modulation. A voltage reference value of 0.8 kV is given and compared with the realtime U_1 to obtain the error, and the error is sent into the voltage outer loop PI controller to output I_{ref} to calculate how much current is needed to correct the voltage. Then the real-time inductor current i_L is compared with I_{ref} to obtain the error, and the error is sent into the current inner loop PI controller to output the duty cycle control variable D . The duty cycle D is compared with a triangular carrier of 6.4 kHz, if the carrier is larger, a high level is output, and if the carrier is smaller, a low level is output, to generate the driving signal to drive the main circuit operation.

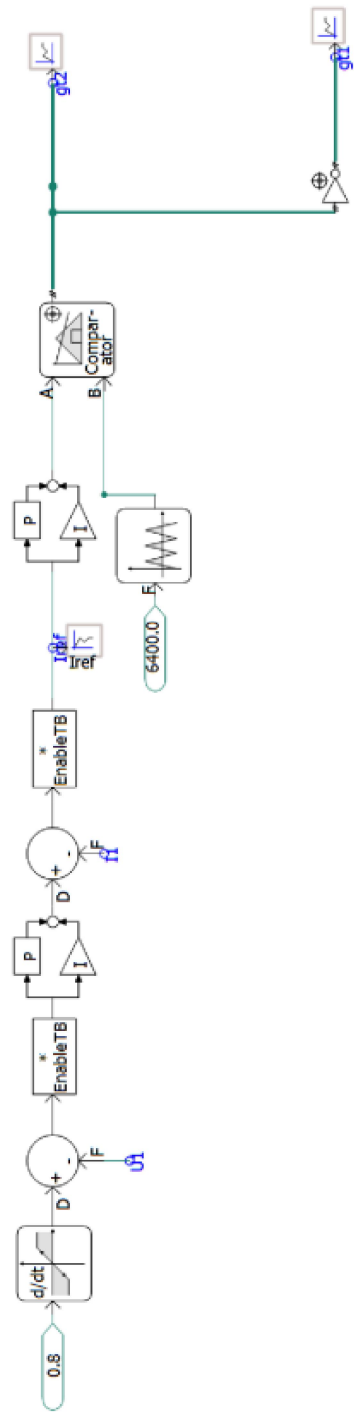


Figure 52: Control system of bidirectional Buck-Boost

4.3 Energy Storage Bidirectional AC/DC Converter and Its V/f Control Strategy

4.3.1 DC/AC Converter Modeling and V/f Control Principle

Eqs. (4.3.1.1)–(4.3.1.3) describe the active and reactive power calculation, the dq-axis current model, and the voltage reference with feedforward decoupling for the DC/AC converter. The energy storage converter uses a three-phase voltage source inverter topology with a six-switch structure, converting the DC bus voltage into three-phase AC. u_a, u_b, u_c are three-phase voltages, i_a, i_b, i_c are three-phase currents, and u_d, u_q, i_d, i_q are the d -axis and q -axis voltages and currents obtained after Park transformation. U is the peak value of the phase voltage. The active power and reactive power are [22]:

$$\begin{cases} P_b = \frac{3}{2}(u_d i_d + u_q i_q) = \frac{3}{2}U_d i_d \\ Q_b = \frac{3}{2}(u_q i_d - u_d i_q) = -\frac{3}{2}U_q i_q \end{cases} \quad (4.3.1.1)$$

Overall model:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L} & \omega \\ -\omega & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{u_d}{L} \\ \frac{u_q}{L} \end{bmatrix} - \begin{bmatrix} \frac{u_{rd}}{L} \\ \frac{u_{rq}}{L} \end{bmatrix} \quad (4.3.1.2)$$

Introducing feedforward decoupling control, the voltage setpoint can be expressed as:

$$\begin{cases} u_{rd}^* = \left(-K_p + \frac{K_i}{s}\right)(i_d^* - i_d) + \omega L i_q + U \\ u_{rq}^* = \left(-K_p + \frac{K_i}{s}\right)(i_q^* - i_q) - \omega L i_d \end{cases} \quad (4.3.1.3)$$

The system uses V/f control, as shown in the Figure 53. A dual closed-loop control is adopted, with the voltage outer loop taking the bus voltage as the reference value, comparing it with the voltage reference value, and maintaining system stability after PI regulation.

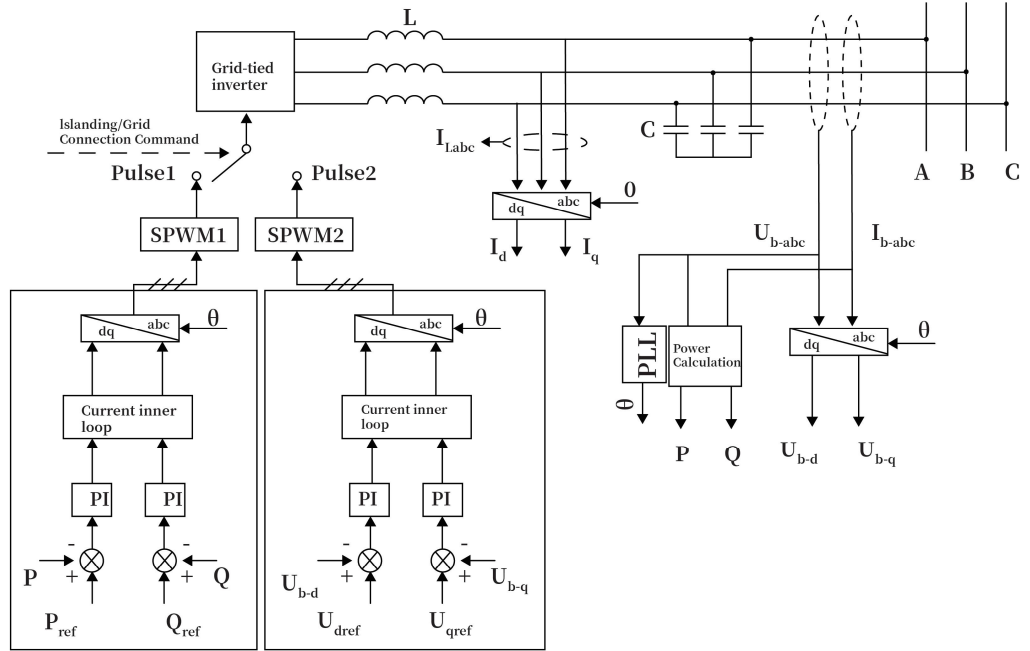


Figure 53: CS system inverter control principle

4.3.2 Simulation of a DC/AC converter in PSCAD

Figure 54 shows the main circuit of the DC/AC converter. The leftmost side is the grid side output terminal, where a $100\ \mu\text{F}$ AC side shunt filter capacitor C is used to stabilize the output voltage, and a grid connected filter inductor L is used to suppress high frequency harmonics. The middle part is a three phase full bridge inverter composed of six IGBTs and anti-parallel diodes. The rightmost side is the DC-link capacitor and the DC bus positive terminal DCP and negative terminal DCN . The SPWM generated gating signals are used to control the switching states of the six IGBTs. By high frequency switching of the power devices, a sinusoidal waveform is synthesized at the output.

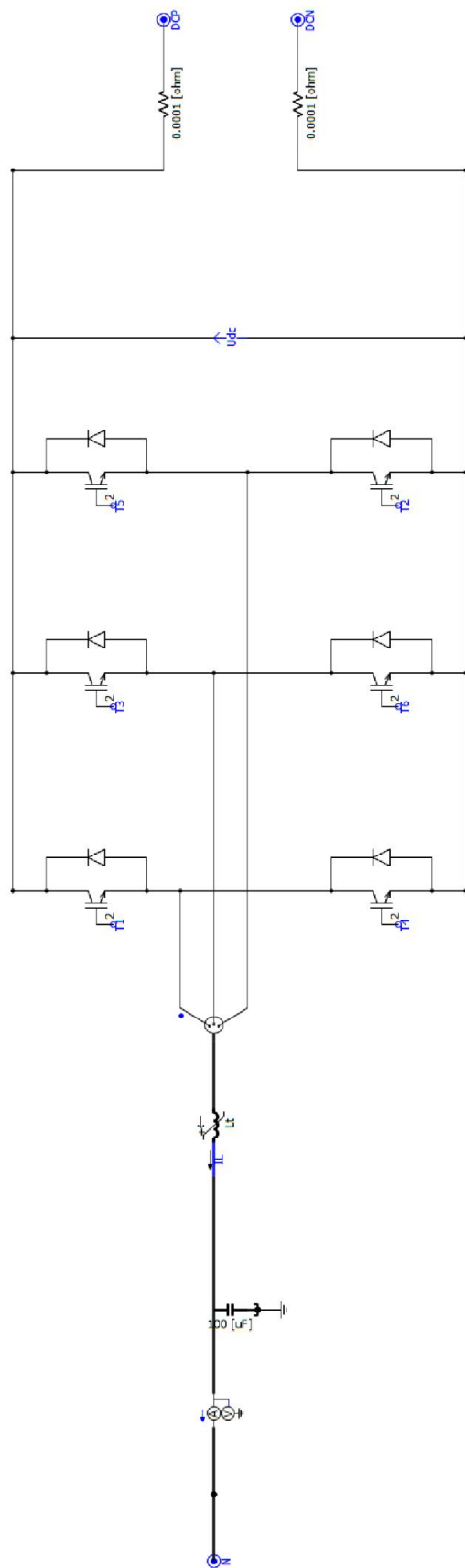


Figure 54: Three-phase voltage source inverter

First, standardize the current, voltage, frequency, and rated capacity per unit as shown in Figure 55. Then, the DC quantity is normalized, and then a three-phase reference voltage is generated. Through the Park transformation as shown in Figure 56, the three-phase quantity is converted into the dq coordinate system, and then decoupling control is performed in a dual-loop, obtaining the d -axis and q -axis quantities. Finally, the inverse Park transformation restores it to three-phase voltage as shown in Figure 57, which enters the SPWM stage to generate the drive pulses.

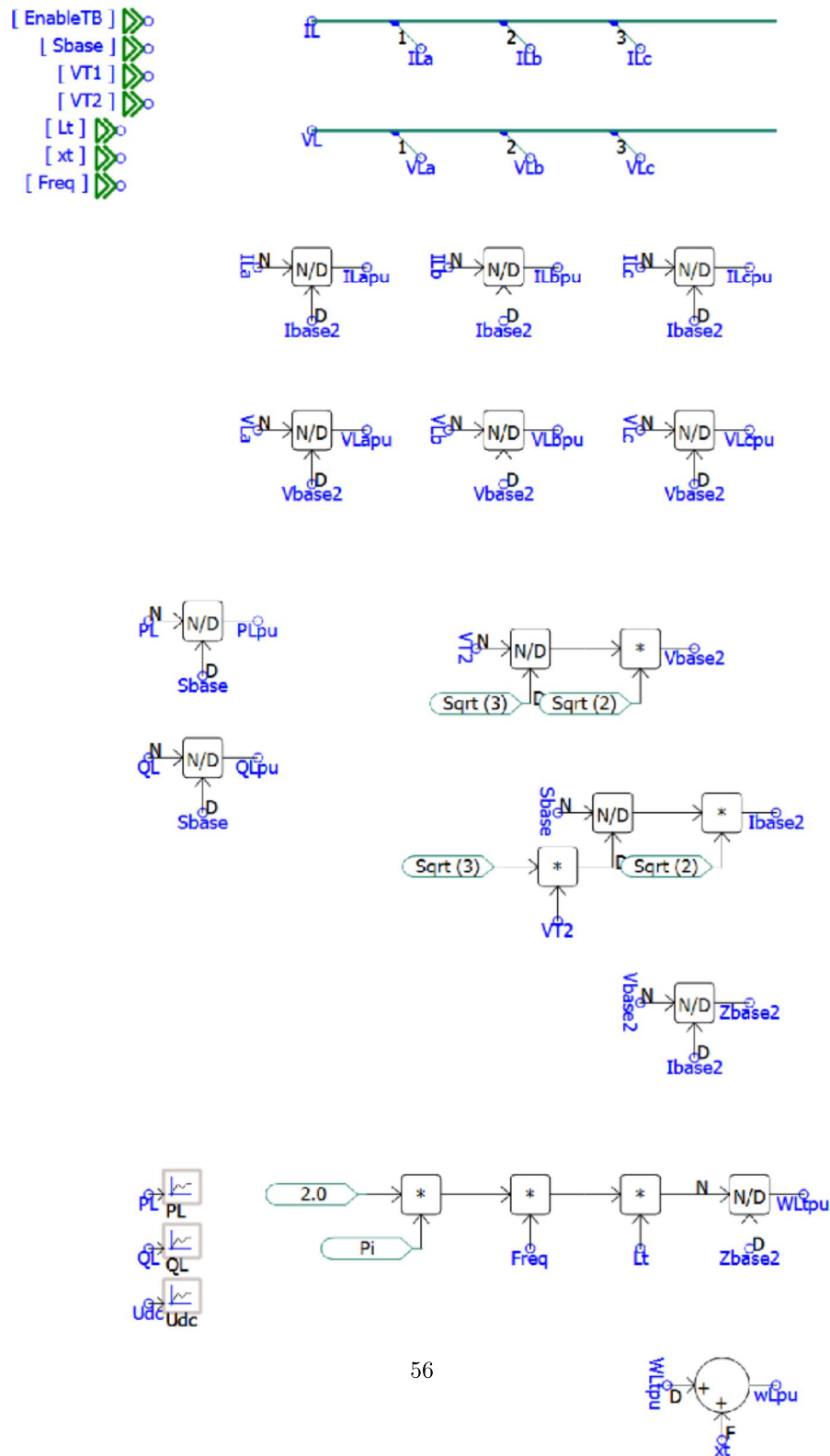


Figure 55: Per-unit normalization

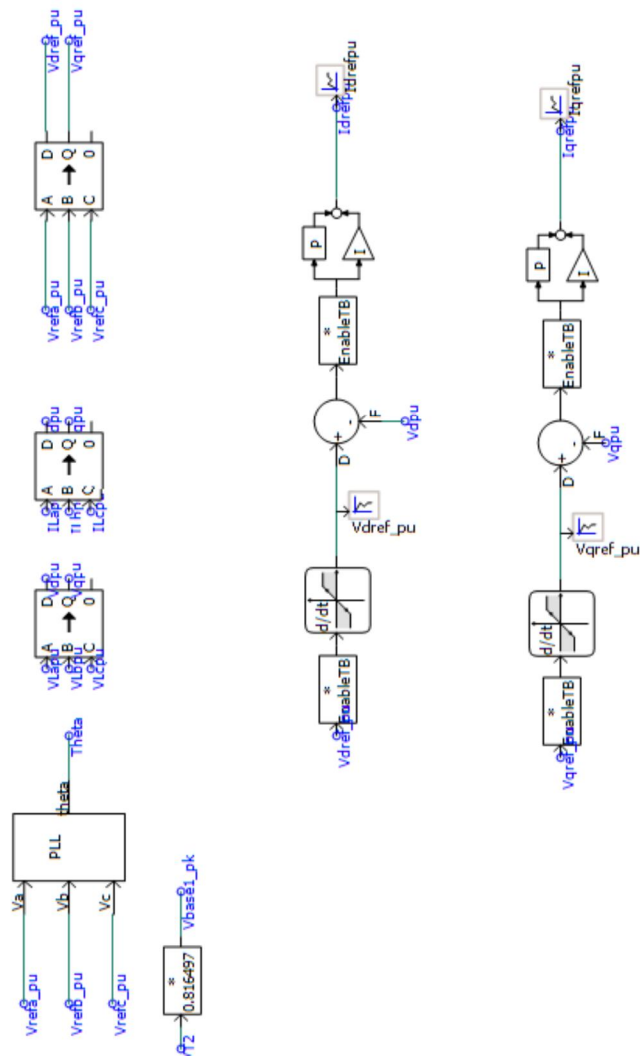


Figure 56: Park Transformation and Dual Closed-loop Control

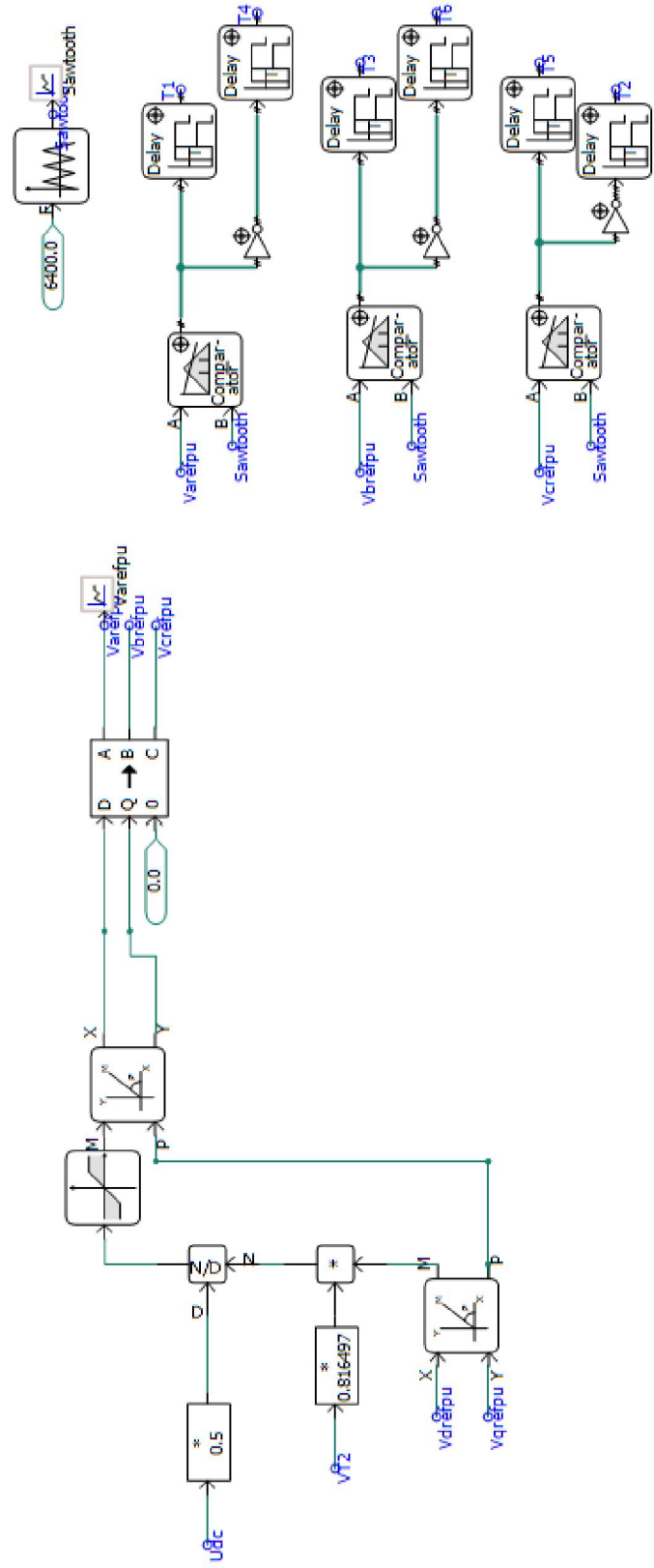


Figure 57: Park inverse transformation and SPWM modulation

5 Coordinated Control Strategy for an Island Wind-PV-Battery Hybrid Microgrid

In the island microgrid operating mode, because the system is not connected to the main grid and there is no backup from the main grid, in order to ensure the stability of the microgrid's voltage and frequency, this thesis uses V/f control [23] for the energy storage to undertake the grid formation task. Wind power and photovoltaic are grid-connected power sources that use PQ control [24], responsible for controlling the output of active and reactive power. The energy storage part that constructs the grid can choose a large capacity energy storage system. The energy storage inverter, as the main grid forming unit, undertakes the task of establishing bus voltage and system power, and also balances the active and reactive power of the microgrid system. Wind turbines and photovoltaic systems, as grid following units, follow the voltage and frequency established by the energy storage to output the given power.

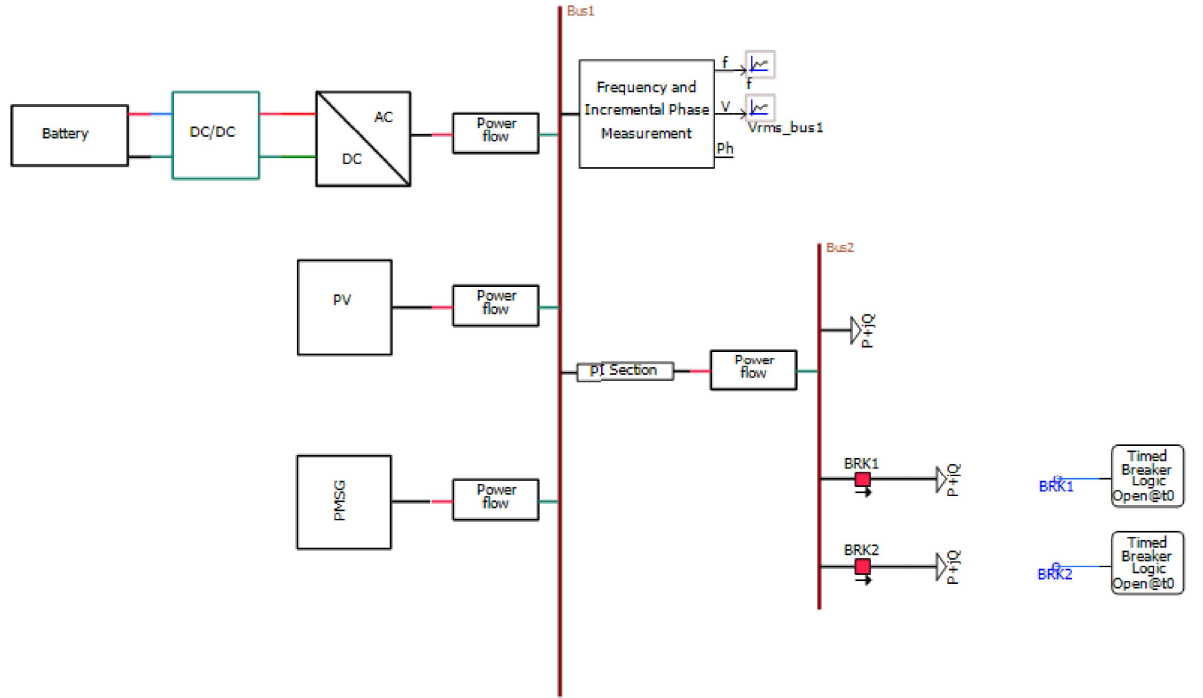


Figure 58: Overall system

The system sets three groups of fixed loads as shown in Figure 58. The base load is always in operation, and the other two loads are controlled by circuit

breakers BRK1 and BRK2 to control their connection times, achieving phased power increase. The base load is 60 kW. At 2 s, BRK1 closes, and the second load level is connected, increasing the load power by 190 kW, with a total load power of 250 kW. At 4 s, the third load level is connected, increasing the load power by 45 kW, with a total load power of 295 kW.

The wind turbine provides the basic active power, the photovoltaic system provides the main active support during the day, and the energy storage system compensates for the power difference.

$$P_{\text{wind}} + P_{\text{PV}} + P_{\text{bat}} = P_{\text{load}} + P_{\text{loss}} \quad (5.1)$$

$$P_{\text{wind}} + P_{\text{PV}} > P_{\text{load}} \quad (5.2)$$

When this occurs, the energy storage system charges.

$$P_{\text{wind}} + P_{\text{PV}} < P_{\text{load}} \quad (5.3)$$

When this occurs, the energy storage system discharges.

The system workflow diagram Figure 59 is as follows. At the start, the energy storage system is activated, establishing the AC bus voltage and frequency. The wind turbine is connected, outputting approximately 125 kW of power at the rated wind speed of 11 m/s. The initial load is 60 kW, and the energy storage system absorbs the excess power. After 2 seconds of simulation, the load increases by 190 kW. The photovoltaic system is then activated and operates at a rated irradiance of 1000 W/m² and a temperature of 25 °C, outputting approximately 125 kW of power. At this point, the total output power of the wind turbine and photovoltaic system is approximately equal to the total load, and the energy storage system neither charges nor discharges. After 4 seconds, the load increases by 45 kW. Now, the total power output from the wind turbine and photovoltaic system is less than the load, and the energy storage system compensates for the power deficit by discharging. The total simulation time is 6 seconds.

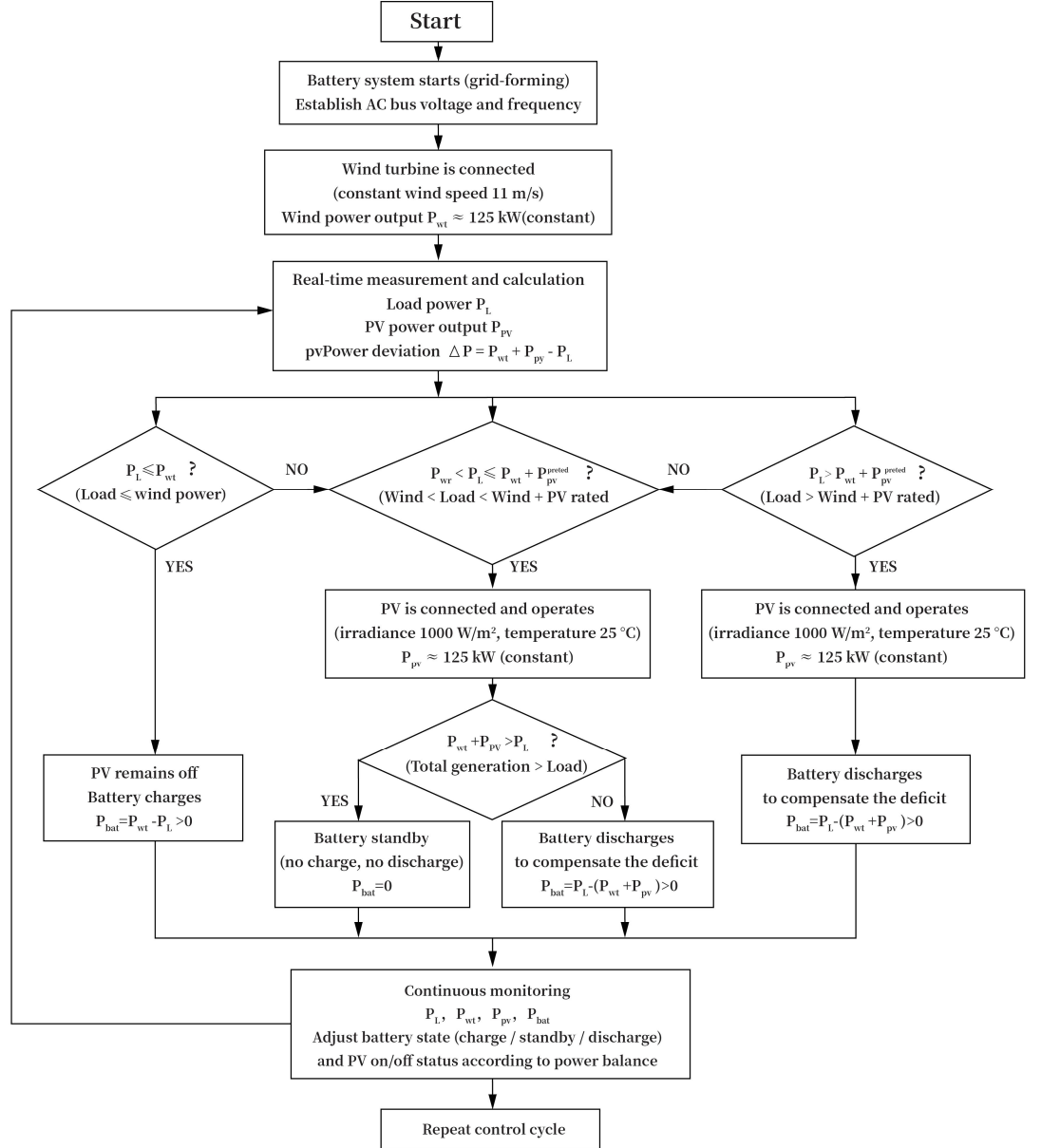


Figure 59: Flowchart of Microgrid Power Generation

6 Simulation Results Analysis

This chapter presents and analyzes the simulation results. Some of the data in the figure are per-unit values, with a base voltage of 400 V and a frequency of 50 Hz.

6.1 Load

Figure 60 shows the load power of the system. According to the plan, the load increased by 190 kW at 2 seconds from 60 kW, and increase to 295 kW at 4 seconds, providing driving conditions for the changes in energy storage, photovoltaics, and wind turbines.

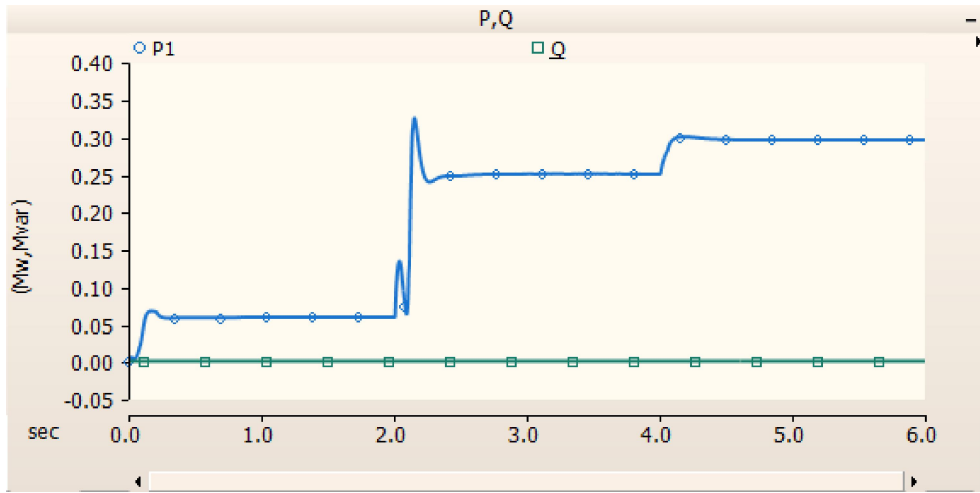


Figure 60: Load power

6.2 Bus

Figure 61 and 62 show the bus frequency and bus voltage of the system. The results show that the bus frequency remained at 50Hz throughout the process, with only slight fluctuations when the load changed. At 2 seconds, when the load increased by 190 kW, the frequency briefly dropped, then quickly recovered, and returned to the original 50 Hz after a slight overshoot. After brief fluctuations of the bus voltage at 2 and 4 seconds, it finally returned to the rated value, indicating that the system is stable.

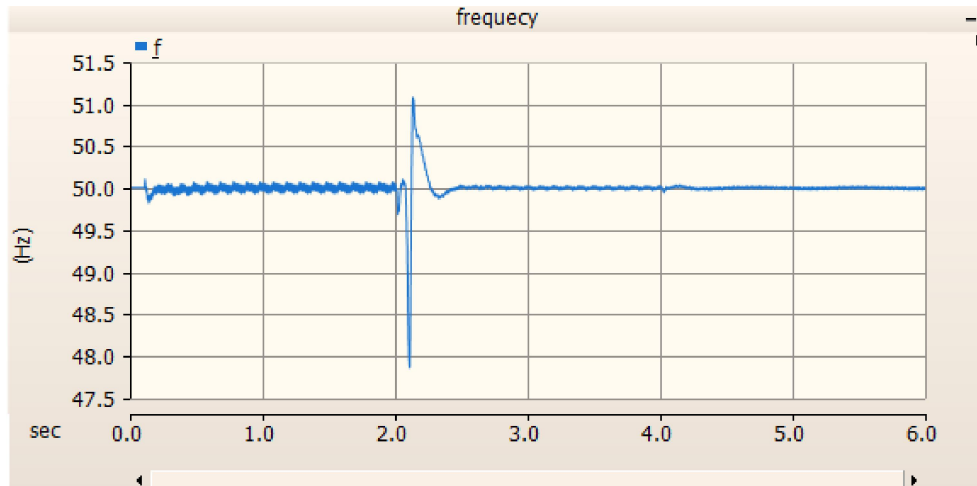


Figure 61: Bus Frequency

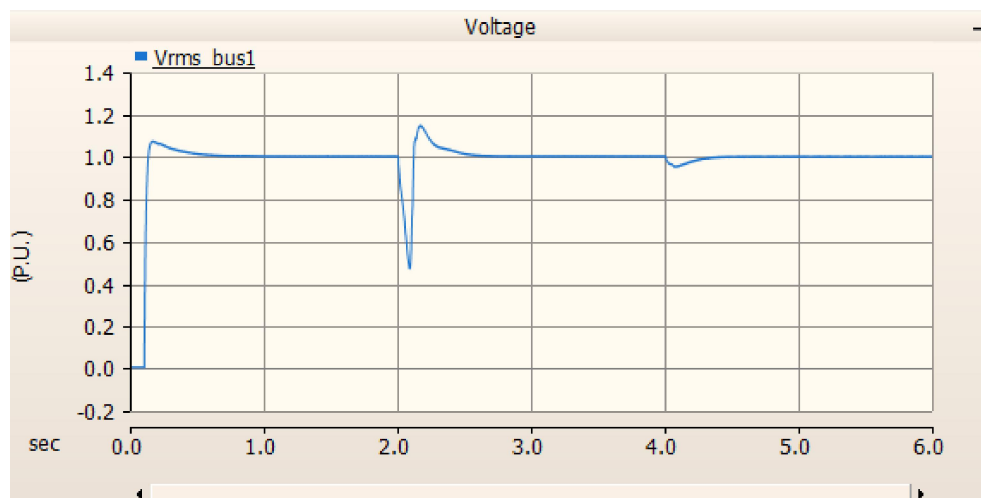


Figure 62: Bus Voltage

6.3 Energy storage

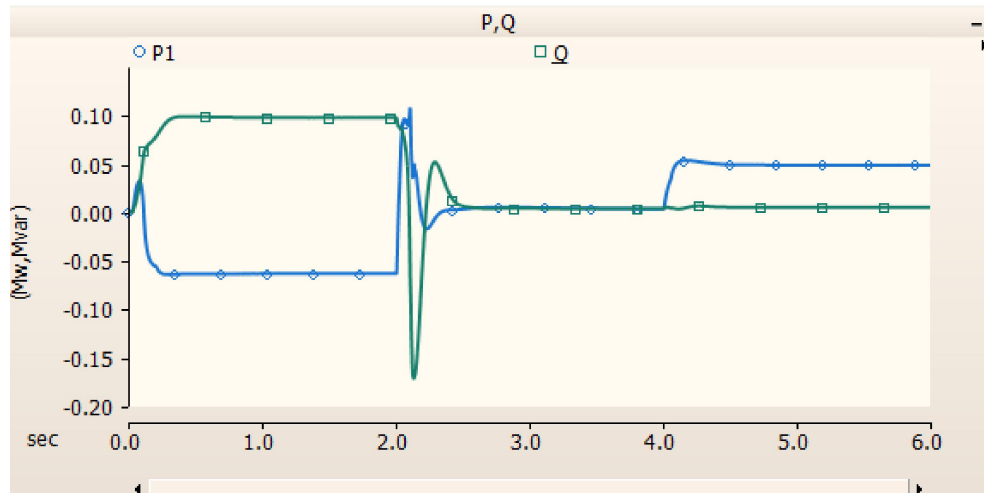


Figure 63: Active and reactive power of the energy storage system

Figure 63 shows the active and reactive power of the energy storage system. At the beginning, the energy storage absorbs excess power to charge. At 2 seconds, it stops charging to maintain system balance. At 4 seconds, it discharges to make up for the power deficit. In terms of SOC in Figure 64, the energy storage slightly increases during charging. It slightly decreases when the load increases and during discharging, quickly responding to load changes.

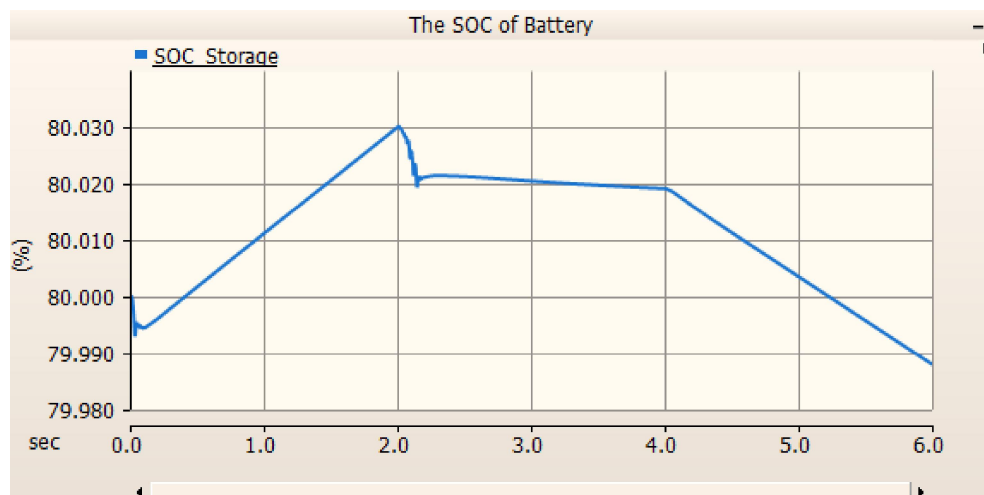


Figure 64: Battery SOC

6.4 Photovoltaic

Figure 65 shows the photovoltaic output power. After the photovoltaic system is connected at 2 seconds, the active power quickly rises to meet the demand and then rapidly stabilizes. Figure 66 shows d-axis current tracking of the photovoltaic system. The d-axis current quickly tracks the reference voltage, showing only a brief overshoot before rapidly stabilizing. Figure 67 shows d-axis current tracking of the photovoltaic system. The q-axis current exhibits the same characteristics. The DC-side voltage of the photovoltaic system quickly follows the reference voltage V_{mppt} as shown in figure 68, stabilizing around 0.42 kV after a brief fluctuation, indicating the effectiveness of the MPPT control. The temporary decrease in reactive power Q during the connection process is mainly caused by the transient charging and discharging of the DC-link capacitor and the filter capacitor in the photovoltaic converter. At the moment when the photovoltaic system is connected, these capacitors introduce a short capacitive reactive current, which causes Q to deviate from its reference value. As the PLL and the current control loop gradually reach steady state, the q-axis current is regulated back close to zero, and the reactive power returns to approximately 0 Mvar. This indicates that the photovoltaic inverter operates close to unity power factor after the transient process.

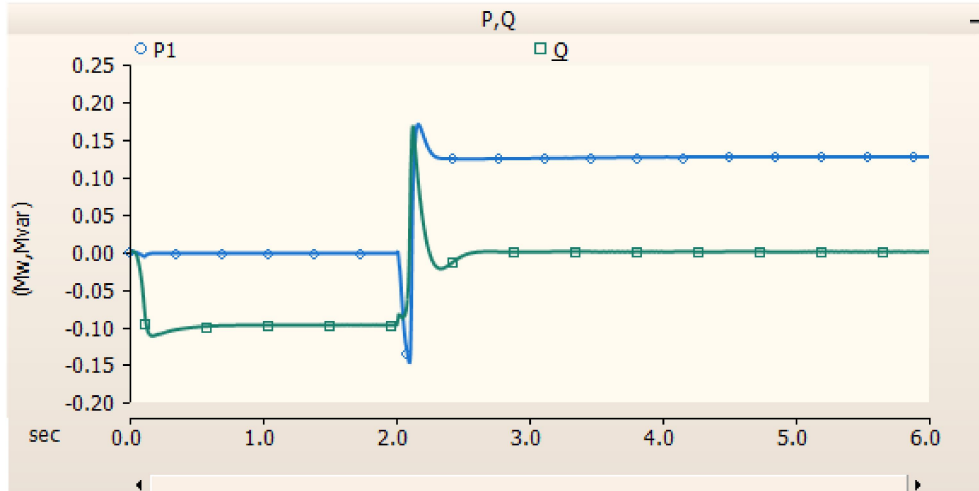


Figure 65: Photovoltaic output power

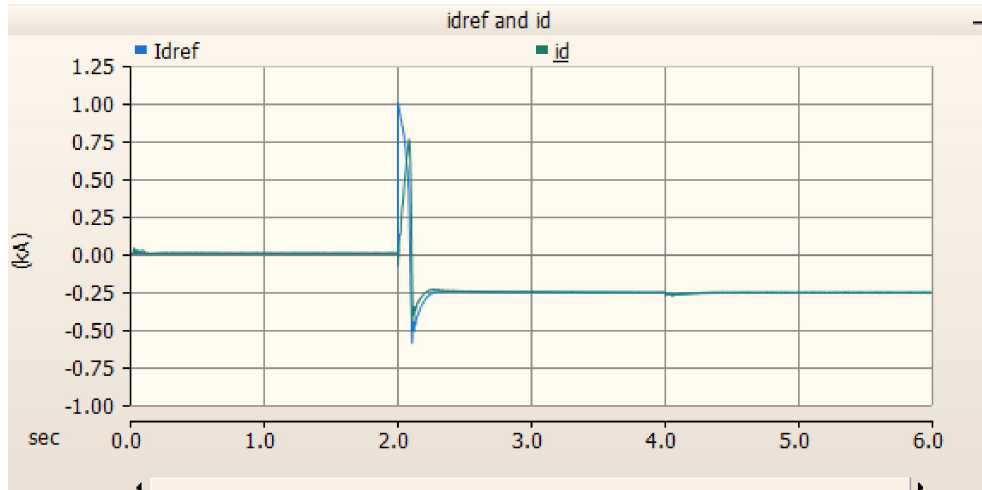


Figure 66: d-axis current tracking of the photovoltaic system

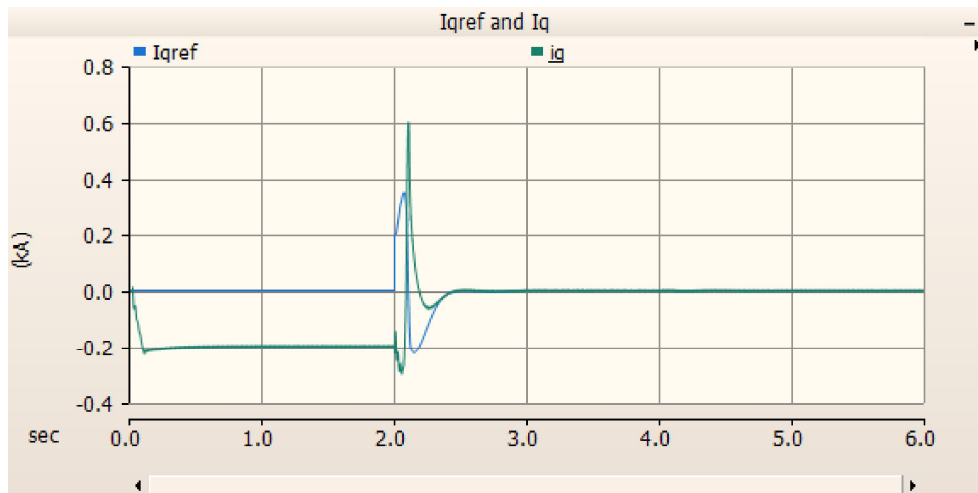


Figure 67: q-axis current tracking of the photovoltaic system

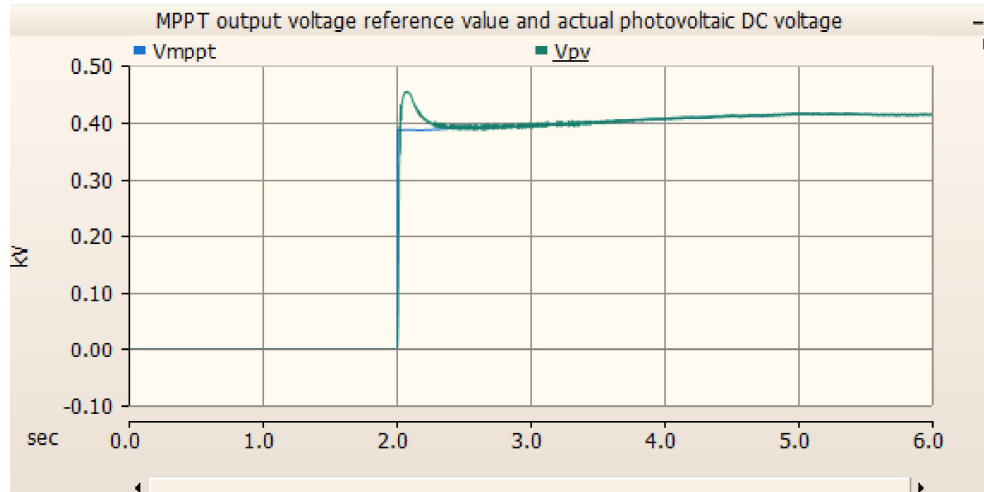


Figure 68: MPPT tracking

6.5 PMSG

Figure 69 shows the turbine power. During the system start-up phase, the wind turbine quickly reaches its rated output power of 0.125 MW. There is a brief fluctuation at 2 seconds, after which it quickly recovers and remains stable, demonstrating the feasibility of constant speed control.

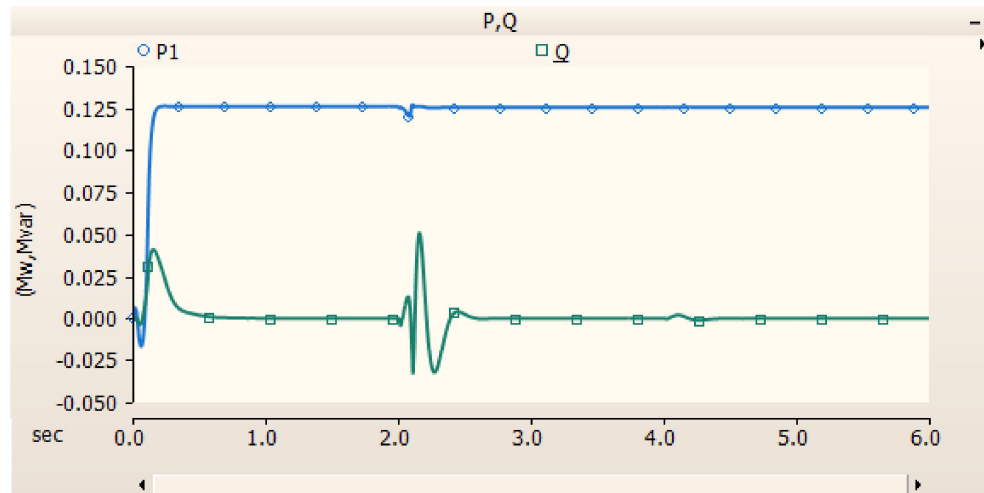


Figure 69: Turbine power

6.6 Chapter Summary

The previous part analyzed the simulation results of the island microgrid in PSCAD. The simulation results show that the system runs stably under different load conditions. This shows that the coordinated control strategy of the photovoltaic system, wind turbine, and battery proposed in this thesis is feasible.

At the initial stage of the simulation, from 0 to 2 s, the load is small. The output power of the wind turbine is greater than the power required by the load. At this time, the energy storage system is charging and absorbs the extra power generated by the wind turbine.

When the simulation reaches 2 s, the load suddenly increases from 60 kW to 250 kW. At the same time, the photovoltaic system is connected to the microgrid. Because of the rapid injection of photovoltaic power, the MPPT tracking process, and the power redistribution inside the system, the photovoltaic output power, dq axis currents, DC side voltage, and bus voltage and frequency show short transient fluctuations.

However, the fluctuation amplitude is small and the duration is short. After that, all variables recover quickly and become stable in a very short time. This shows that the photovoltaic control system has good tracking ability. It also shows that the V/F control of the energy storage system can effectively support the voltage and frequency of the microgrid.

At 4 s, the load further increases to 295 kW. The total output power of the wind power and photovoltaic power is smaller than the load power. Therefore, the energy storage system changes from the balanced state to the discharging state.

In this simulation, the bus frequency is maintained at 50 Hz, and the voltage is basically maintained at 0.4 kV. After being affected by the photovoltaic grid connection, the system can also quickly recover to a stable value.

Overall, the simulation results verify that the proposed coordinated control strategy of wind power, photovoltaic power, and energy storage can effectively maintain the power balance, voltage stability, and frequency stability of the island microgrid.

7 Conclusion

Under the global advocacy for low-carbon and sustainable development, clean energy such as photovoltaic and wind power is increasingly gaining importance. In some practical engineering scenarios, such as remote and weak-grid or off-grid areas, where it is not possible to connect to the main grid, studying the composition of wind-solar-storage microgrids under local existing conditions has practical significance. This paper mainly studies the operational stability of the wind-solar-storage microgrid under short-term large load variations. We built wind power generation, photovoltaic power generation, energy storage battery systems, and load in PSCAD. The wind power generation system uses a permanent magnet synchronous generator model, the photovoltaic system uses MPPT control for maximum power point tracking, and the energy storage system realizes charging and discharging through a bidirectional converter and supports the voltage and frequency of the island microgrid with V/F control. Wind turbines and photovoltaic systems serve as power output units, while energy storage supports the voltage and frequency as a supporting unit, jointly achieving system power coordination control. The feasibility of this control strategy is verified through simulation.

However, there are still some shortcomings in this thesis. Due to time limitations and the scope of this study, only a small microgrid model was built through theoretical analysis in PSCAD, mainly analyzing the system's response within a short period of time. Further research on energy management under long-term operation has not been conducted. Additionally, in this thesis, wind speed, solar irradiance, and temperature, and load variations are idealized. Future work can further strengthen the model in this study, such as considering more complex operating conditions, variations in irradiation, temperature, wind speed, and different battery state of charge under disturbances. Further research on the configuration of wind-storage systems can also be developed.

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