International Journal of Frontiers in Engineering Technology
ISSN 2706-655X Vol.6, Issue 3: 9-17, DOI: 10.25236/IJFET.2024.060302

Simulation Research of Low-Carbon Multi-Scenario Home Energy Management System in Smart Grid Environment

Tong An

Beijing Forestry University, Beijing, 10083, China

Abstract: *In order to address the shortcomings of the traditional power grid, the concept of a home energy management system has been proposed and studied to achieve the goals of improving electricity consumption efficiency, energy conservation, and emission reduction. This paper aims to explore low-carbon multi-scenario home energy management and control strategies, construct a photovoltaic energy storage system using Simulink, integrate it with the constructed home load and grid, and realize low-carbon control of home energy. It also investigates energy management and control by simulating power supply variations with changing home loads and assesses the feasibility of this system. The system considers solar photovoltaic (PV) and battery new energy as primary inputs and develops a maximum power point tracking (MPPT) algorithm for PV energy to ensure maximum PV system efficiency. Electrical load scheduling algorithms are designed to optimize energy utilization while ensuring power supply and reducing energy consumption. Energy storage battery systems are considered to balance energy supply and demand, with lithium-ion batteries selected to optimize system energy storage efficiency. An intelligent energy management and control strategy is developed to build a low-carbon multi-scenario home energy management and control system in an intelligent power network environment, considering factors such as PV energy, battery status, and electrical load demand.*

Keywords: *Low-carbon new energy, photovoltaic energy storage, home energy management, intelligent control, multi-scenario load analysis*

1. Introduction

China's strategic plan of "dual-carbon" targets makes energy revolution imperative. Current research on home energy management systems takes into account modeling, protection, and optimal scheduling of a high percentage of clean energy power systems. Photovoltaic (PV) power generation is being promoted in China due to its cleanliness, efficiency, and sustainability, and is one of the fastest-growing energy sources in various energy structures in China [1]. PV energy storage energy management systems generally consist of PV modules, grid-connected inverters, lithium batteries, AC-coupled storage inverters, smart meters, current transformers (CT), grids, and control systems. The basic principle is to utilize the photovoltaic effect to convert solar radiation into direct current (DC) electrical energy, and then store the electrical energy through an energy storage device [2]. Under the low-carbon trend, low-carbon energy sources such as solar energy and wind energy are gradually entering the field of home energy, and home energy is developing towards low-carbon and multi-energy mixed use [3], to realize efficient use of solar energy and continuous energy supply.

However, there are still some problems with home energy management systems that need to be studied and improved. For example, reactive power and voltage problems arise after connecting to the PV power supply. The voltage at each load node along the feeder is elevated due to the reduction of transmitted power on the feeder, which may lead to voltage overshoot at some load nodes. Insufficient reactive power not only results in voltage drop but also contributes to voltage instability, and in severe cases, voltage collapse [4]. Harmonic problems occur when distributed generation via power electronic inverters connected to the grid generates harmonics, three-phase voltage or current imbalances, and the randomness of output power makes the grid susceptible to voltage fluctuations and flicker [5]. If distributed power supply is directly connected to the grid on the user side, power quality problems directly affect the safety of users' electrical equipment. Problems arising from bidirectional current flow stem from the traditional unidirectional current flow in distribution networks. Historically, distribution networks have solely received loads. However, with the proliferation of distributed PV power generation connections, the traditional radial passive distribution network undergoes a transformation into an active network replete with small and medium-sized power sources. Consequently, current flow within the distribution network transitions from unidirectional to bidirectional, precipitating a shift in network topology from a singular radial structure to a complex mesh topology featuring loops [6].

The system constructed in this research project aims to focus on the above problems of the traditional home energy management system, and research on the maximum power tracking algorithm (MPPT), harmonic elimination, phase-locked loop technology (PLL), etc., and build a clean, efficient, green, and low-carbon multi-scenario home energy management control system using MATLAB R2023a Simulink software.

2. Technical program of the study

2.1. Main content of the study

In recent years, countries around the world have launched numerous policies to promote photovoltaic power generation as a clean, renewable green energy source [7]. Strong support for the construction of the solar photovoltaic industry and the rapid development of the industry provides strong policy support. Photovoltaic power generation helps to save and optimize investment in the distribution network, and is an important measure to achieve the goals of "Carbon Peak, Carbon Neutral" and rural rejuvenation.

The low-carbon multi-scenario home energy management system constructed in this research project considers PV and battery new energy as the main inputs to the system and develops a maximum power point tracking (MPPT) algorithm for PV energy to ensure maximum efficiency of the PV system [8]. Electrical load scheduling algorithms are designed to optimize energy utilization while ensuring power supply and reducing energy consumption. Energy storage battery systems are considered to balance energy supply and demand, with lithium-ion batteries selected to optimize system energy storage efficiency [9]. An intelligent energy management control strategy is developed, considering factors such as photovoltaic energy, battery status, and electrical load demand.

According to the simulation results and operation of this system, the low-carbon multi-scenario home energy system can help the AC grid to share the home load during peak load periods, reducing power transmission of the AC grid and reflecting the new development concept of low-carbon and environmental protection. The system improves grid stability and power supply quality while realizing the sustainable use of energy. This low-carbon multi-scenario home energy management system provides an intelligent, efficient, and sustainable energy management solution for households by integrating new energy sources, electrical load management, and intelligent control strategies, improving quality of life, reducing energy waste, and positively impacting the environment.

The overall model of the low-carbon multi-scenario home energy management system built in this research project is shown in *Figure 1*:

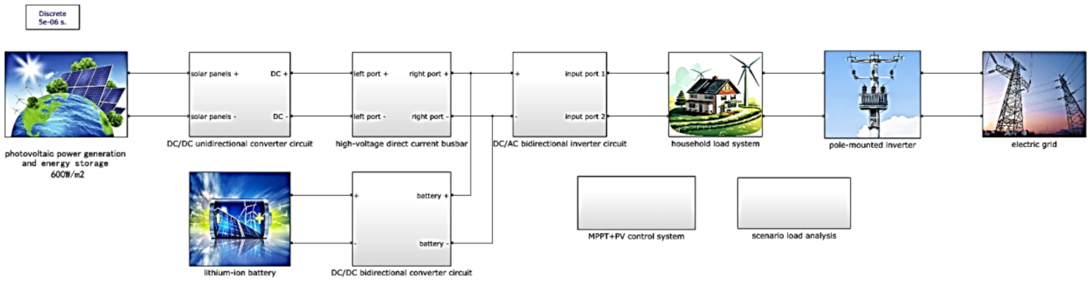

Figure 1. Model of low carbon multi-scenario home energy management system

This low-carbon multi-scenario home energy management system optimizes home energy consumption by managing various energy sources such as renewable energy, grid power, and energy storage devices, including solar PV power generation and energy storage, DC/DC unidirectional and bidirectional converter circuits, high-voltage busbar transmission networks, DC/AC bidirectional rectifier inverter circuits, multiple control systems, battery modules, and grid systems, and conducts multi-scenario analysis of home electricity loads to optimize energy management control and improve low-carbon energy utilization.

2.2. Scientific and Rationality Study of the System

Photovoltaic power generation systems harness solar energy to convert it into electricity, constituting a renewable energy source. This approach diminishes reliance on traditional energy sources and aids in curtailing carbon emissions, aligning with the objectives of low-carbon living and sustainable development [10]. The battery system is capable of storing excess electrical energy generated by the PV system during the day for use at night or during periods of low energy output. This energy storage and balancing mechanism effectively manages the volatility of PV energy and enhances energy utilization efficiency. By generating, storing, and utilizing electricity within the home, losses in the power delivery process are minimized. The scientific home energy management system employs intelligent control algorithms that integrate the status of PV generation and battery systems to facilitate intelligent energy distribution [11]. This intelligent energy management maximizes system benefits and minimizes energy wastage.

Adopting a photovoltaic battery power solution enables households to embrace a low-carbon lifestyle. It not only reduces dependence on fossil fuels but also mitigates greenhouse gas emissions, positively impacting the environment. Scientifically designed home energy management systems can enhance families' awareness of energy usage and inspire them to adopt a more energy-efficient and eco-friendly lifestyle [12]. With the continuous advancement and maturity of photovoltaic (PV) and battery technologies, the reliability and efficiency of these systems have significantly improved. Moreover, the ongoing development of new materials, more efficient solar cells, and advanced battery technologies continues to propel the evolution of PV battery systems.

This low-carbon multi-scenario home energy management system employs solar PV energy storage with a power rating determined by a current-voltage constant irradiance meter. This ensures a stable power rating and utilizes multiple control circuits to supply power to the home load system [13]. To maximize the utilization of solar energy and achieve substantial carbon emission reduction, the PV cells are optimized to output maximum power under varying environmental conditions. The system employs the MPPT control algorithm, ensuring that the solar PV cells consistently operate at maximum power regardless of the conditions. Additionally, the incorporation of a battery storage system further enhances the utilization of photovoltaic energy. The voltage-current dual closed-loop PID control system is widely employed to regulate voltage and current, ensuring reasonable voltage fluctuations [14].

DC voltage inverters may generate high harmonics, leading to AC grid voltage distortion and instability, which can compromise grid safety and stability. To mitigate this issue, the system incorporates an LC filter to reduce harmonics, thereby improving AC grid power quality and stability [15]. Furthermore, the utilization of a PLL phase-locked loop ensures fixed phase difference values between input and output voltages when their frequencies are equal [16].

As PV and battery technologies continue to advance and mature, they enhance the reliability and efficiency of systems. Sustained technological advancements contribute to the long-term stability and optimization of these systems. Therefore, the rationality of designing low-carbon home energy management systems lies in considering various aspects such as environmental protection, economic viability, social responsibility, and technological progress. This holistic approach provides sustainable and intelligent energy management solutions for households.

3. Research Technology Route

3.1. Low-carbon multi-scenario home energy management system model

The home energy management system developed in this research optimizes energy consumption by managing diverse energy sources, including renewable energy, grid power, and energy storage devices. It encompasses solar photovoltaic power generation, energy storage, DC/DC unidirectional and bidirectional converter circuits, high-voltage busbar transmission networks, DC/AC bidirectional rectifier inverter circuits, multiple control systems, storage battery modules, and the grid system. It analyzes home electricity loads across multiple scenarios to optimize energy management control.

3.1.1. Photovoltaic Power Generation and Energy Storage Modeling

The PV power generation and energy storage model, as depicted in *Figure 2*, features a rated power of 5KW determined by a current-voltage constant irradiance meter. It employs MPPT control to track the maximum power point, a unidirectional DC/DC converter for solar cell implementation, and multiple control system circuits to supply power to the home load system.

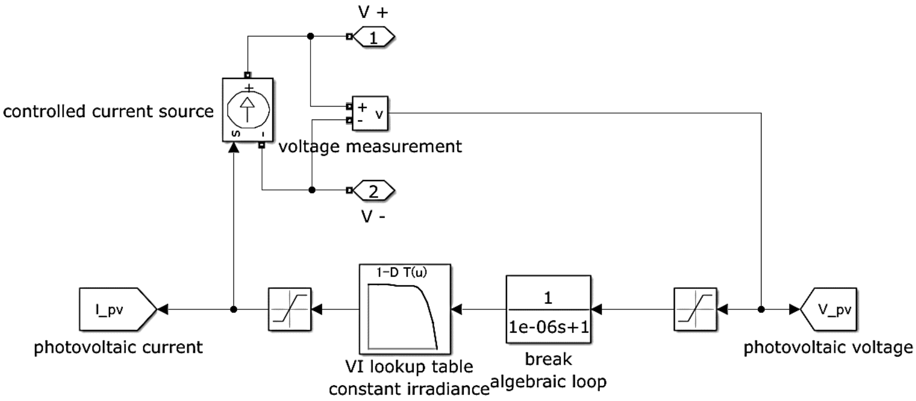

Figure 2. Photovoltaic power generation and energy storage model section

3.1.2. Grid Modeling

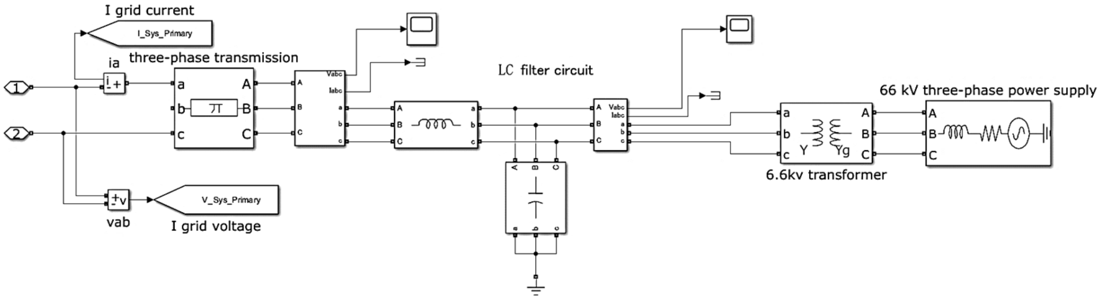

Figure 3. Grid model section

Figure 3 illustrates the grid section connected to the residence through a vertical pole-mounted distribution transformer. This configuration enables surplus power from the home energy management system while supplying power to the system. The grid and home energy system connection is governed by a bidirectional DC/AC rectifier-inverter circuit.

3.1.3. Battery Model

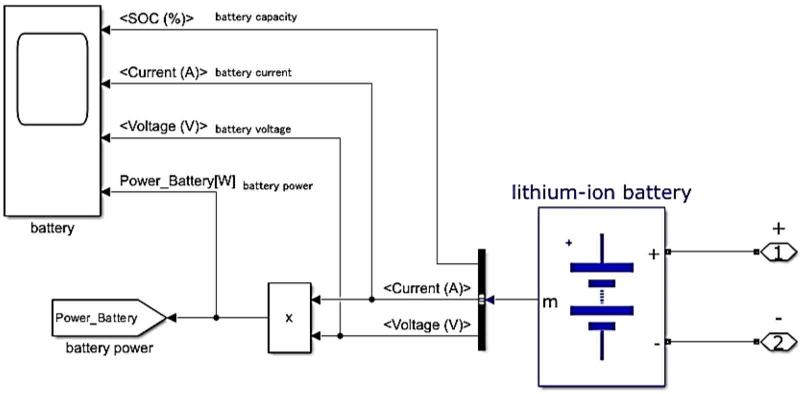

Figure 4. Battery model section

Compared to general chemical batteries, storage batteries are widely utilized in energy conversion and storage due to their ability to store and release energy through various technical means. The model depicted in *Figure 4* employs lithium-ion batteries known for their high cycle times, efficiency, fast charging and discharging, safety, and environmental adaptability.

3.2. Overview of multiple control systems

3.2.1. MPPT control

Figure 5 illustrates the MPPT control systems. The MPPT control in this simulation system utilizes the perturbation observation method. The basic idea is as follows: firstly, perturb the output voltage (or current) of the PV cell, then observe the change in the PV cell's output power. Based on the trend of power change, continuously adjust the direction of the perturbation voltage (or current) so that the PV cell operates at its maximum power point [18].

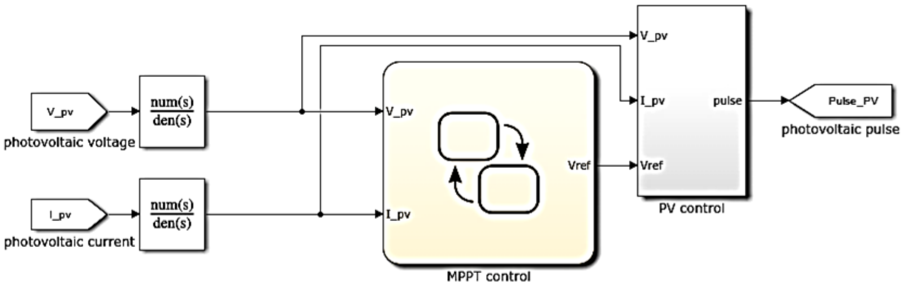

Figure 5. MPPT control system model section

In general, under normal conditions, the P-U characteristic curve of a PV cell follows a single peak function, with the maximum power point as the extreme value. This means that starting from an initial state, each incremental change in the input signal is measured. Then, the size and direction of the output change due to the input signal change are determined. Once the direction is discerned, the control system adjusts the inputs of the controlled object accordingly, steering it towards the desired direction to achieve optimal self-regulation. When applying the step search to the MPPT control of the PV system, it is known as the perturbation observation method. Assuming constant environmental conditions such as irradiance and temperature, when the load characteristics intersect with the characteristics of the photovoltaic cell to the left side of the maximum power point, the MPPT control increases the voltage at the intersection. Conversely, when the intersection is to the right side of the maximum power point, the MPPT control decreases the voltage at the intersection. If the search process continues, the system ultimately tracks to the maximum power point of the photovoltaic cell. Thus, the resulting operating point meets the expectation of the maximum power point.

3.2.2. PV control

The PV control in this simulation system employs voltage-current dual closed-loop PID control, a common method in power electronic systems. This control method consists of a proportional term (P), an integral term (I), and a differential term (D), used to regulate the system's output close to the desired value. *Figure 6* illustrates the specific model.

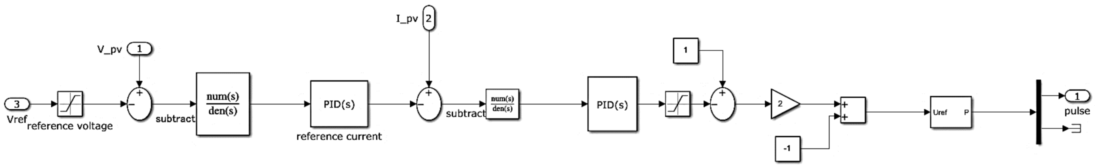

Figure 6. PV control system model section

In voltage-current dual closed-loop PID control, there are typically two closed-loop systems: one for voltage control and the other for current control. The voltage closed-loop control ensures that the output voltage remains stable and conforms to a predetermined value. Its PID controller adjusts the control signals in the voltage control loop to bring the output voltage close to the desired value based on the difference between the actual output voltage and the set value. Similarly, the current closed-loop control ensures that the output current remains stable and conforms to the predetermined value. Its PID controller adjusts the control signal in the current control loop based on the difference between the actual output current and the set value, aiming to make the output current close to the desired value.

The control process of the entire system entails closed-loop control of both voltage and current, facilitating precise control of the power electronic system. The selection and adjustment of PID parameters are critical to the system's performance and necessitate optimization according to specific application and system requirements.

3.2.3. Battery Control

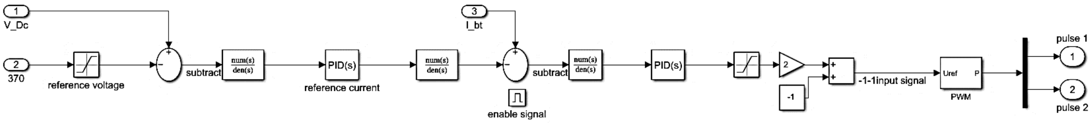

Figure 7. Battery control system model section

The battery control of this simulation system utilizes the same voltage-current double closed-loop PID control, as previously described and not reiterated here. The model depicted in *Figure 7* employs the PWM (Pulse Width Modulation) electronic modulation technique. This technique simulates the amplitude of an analog signal by adjusting the width of the pulse signal while keeping the signal's period constant[19]. The duty cycle, expressed as a percentage, represents the ratio of the pulse width to the entire period. For instance, a 50% duty cycle means the pulse width is half of the entire period.

In this system, PWM modulation employs single pulse modulation, meaning there is only one pulse per cycle, and the analog signal is modulated by varying the pulse width. The resulting PWM signal can be digitally expressed, offering high efficiency.

3.2.4. Inverter control

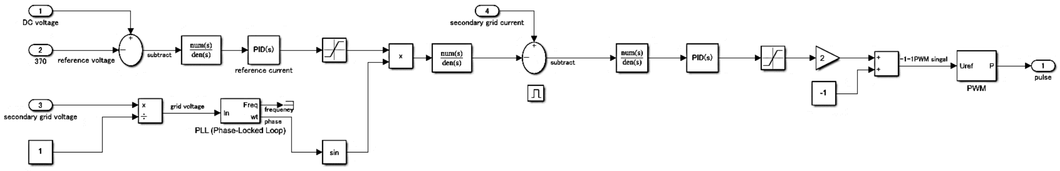

Figure 8. Inverter control system model section

The inverter control system in this simulation integrates a PLL phase-locked loop control system alongside the voltage-current dual closed-loop PID control, as illustrated in *Figure 8.* A PLL is a widely used control system designed to track and maintain the phase difference between the input signal and the local reference signal. Its primary objective is to ensure a stable relationship between the phases of the output and input signals. This is achieved by continuously adjusting the phase and frequency of the output signal to synchronize it with the input signal.

When the phase difference between the input signal and the local reference signal changes, the phase comparator generates an error signal. This signal undergoes filtering through a low-pass filter to generate a smooth control signal. This control signal adjusts the frequency of the Voltage-Controlled Oscillator (VCO) to synchronize it with the input signal and minimize the phase difference. This iterative process continues until the phase difference approaches zero, leading to system stabilization.

4. Multi-scenario household load scenario analysis

4.1. Overview of household load modeling

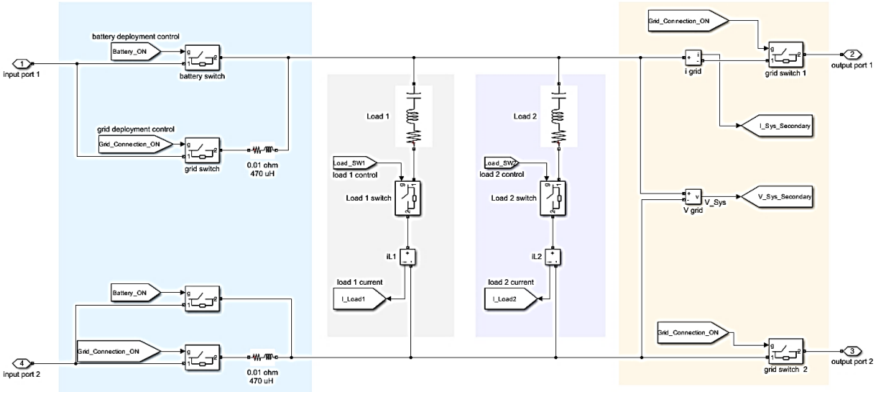

Figure 9. Part of the home load model

The household load depicted in *Figure 9* consists of a single-phase household load, with two 3KW loads connected to the low-carbon multi-scenario household energy management system. When both loads operate simultaneously, they collectively consume 6KW of power. Through the input of these two loads, the model simulates different operational scenarios, enabling the analysis of household low-carbon multi-scenario electricity consumption loads.

4.2. Home low carbon multi-scenario electricity load analysis

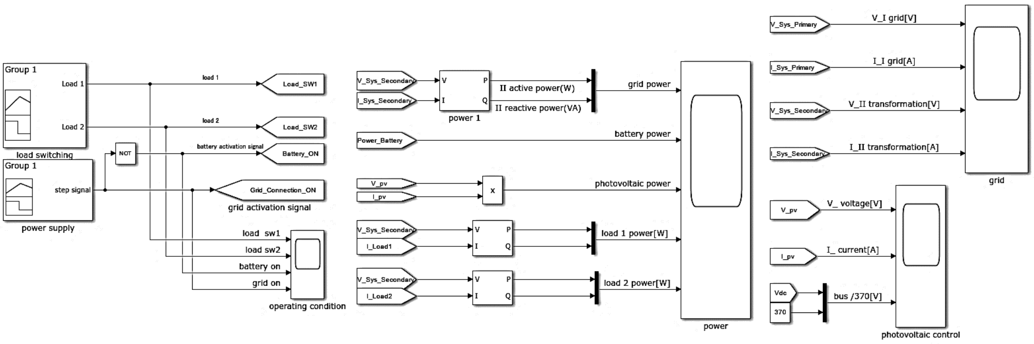

Figure 10. Multi-scenario load analysis model part

Run the simulation model to analyze the load situation of various scenarios depicted in *Figure 10*. This includes examining the behavior of loads, batteries, inverters, as well as the status of PV battery voltage and current, bus voltage, household loads, batteries, PV batteries, and load power. Additionally, assess the voltage and current situation of both the grid and household loads.

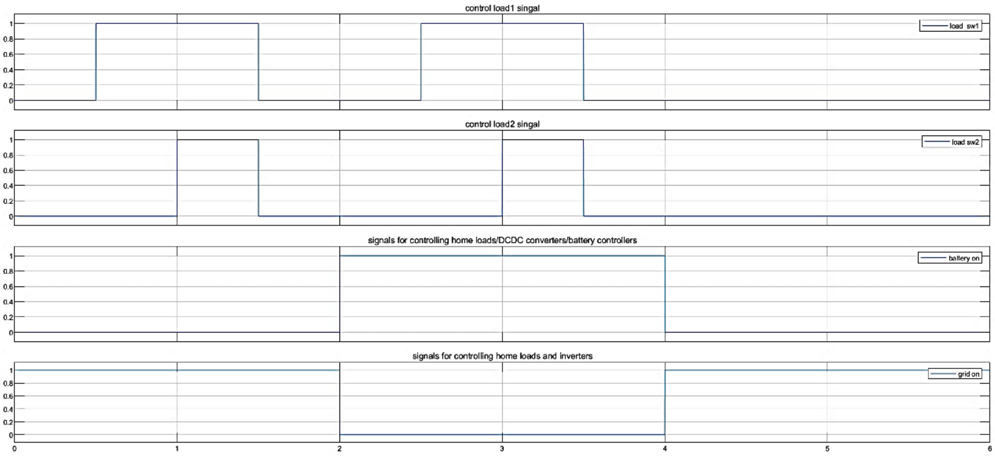

Figure 11. Input signal operation

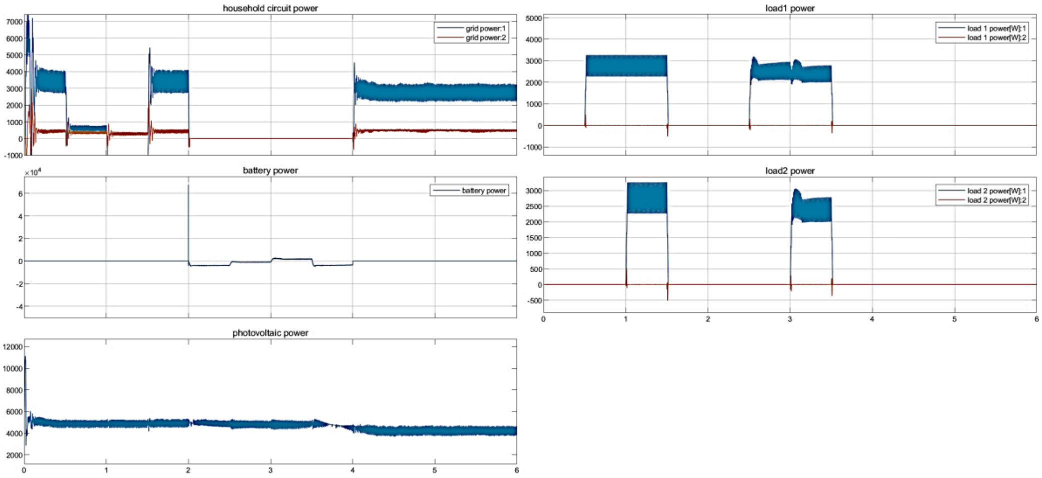

Figure 12. Stage load situation analysis

Based on the results from *Figure 11* and *Figure 12,* the following analysis can be derived: The first stage simulates the ideal scenario of households with no load during nighttime (Scenario I). Both load 1 and load 2 are in a disconnected state, and the battery remains unused. During this period, only the PV power supply in the line operates, providing 5kW of power, with any excess power generated flowing back to the grid.

The second stage represents the ideal scenario of daytime household load with minimal consumption (Scenario I). Load 1 is connected to the line, consuming 3kW of power, while load 2 remains disconnected, and the battery is inactive. The PV power supply in the line provides 5kW of power to load 1, with any surplus energy returned to the grid.

The third stage simulates the ideal scenario of evening and summer peak electricity consumption (Scenario I). Both load 1 and load 2 are connected to the line, consuming a total of 6kW of power, surpassing the 5kW provided by the PV power supply. During this period, the battery remains inactive, and the grid supplements an additional 1kW of power.

The fourth stage represents the ideal scenario of nighttime household load with no consumption (Scenario II). Both load 1 and load 2 are disconnected, and the battery is actively used. Only the PV power supply operates, charging the battery. Once the battery reaches full capacity, any excess power generated by the PV flows back to the grid.

The fifth stage simulates the ideal scenario of daytime household load with minimal consumption (Scenario II). Load 1 consumes 3kW of power from the line, while load 2 remains disconnected, and the battery is utilized. The PV power supply provides 5kW to load 1, with any surplus power directed to charge the battery. Once the battery is fully charged, excess energy flows back to the grid.

The sixth stage represents the ideal scenario of daytime and summer peak electricity consumption (Scenario II). Both load 1 and load 2 are connected to the line, consuming a total of 6kW, surpassing the 5kW provided by the PV power supply. During this period, both the PV circuits and loads are disconnected from the grid, and the battery is utilized to provide an additional 1kW of power.

5. Conclusions

This research project aims to develop a low-carbon multi-scenario home energy management simulation system, facilitating the implementation of low-carbon energy control at home. It investigates energy management strategies by simulating various power supply scenarios corresponding to changes in home load. By leveraging photovoltaic (PV) and storage battery as primary energy sources, the system integrates a maximum power point tracking (MPPT) control disturbance observation algorithm for PV energy. Additionally, it incorporates an energy storage battery system to balance energy supply and demand, with a focus on optimizing storage efficiency through the selection of lithium-ion batteries. Moreover, the system formulates an intelligent energy management control strategy.

By enabling the AC grid to share household load during peak demand periods, the system effectively reduces power transmission losses and aligns with the low-carbon and environmental protection concept. Furthermore, it enhances grid stability and power supply quality while promoting sustainable energy utilization. Ultimately, this system offers an intelligent, efficient, and sustainable energy management solution for households, contributing to improved quality of life and positive environmental impact.

Acknowledgements

Beijing Forestry University.

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