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Multi-Objective Optimized Energy Management System for Nano-grids

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Abstract. With the incessant growth in energy demand and dwindling energy resources, the need for efficient energy management systems for sustainable development has become paramount. Emerging alongside the rise of renewable energy technologies, nano-grids offer an innovative approach to energy distribution. To cater to the unique intricacies and variable nature of nano-grids, we've designed a multi-objective optimized energy management system. A refined particle swarm optimization (PSO) algorithm, tailored specifically for these systems, has been proposed and implemented on an embedded platform. The paper delves into the design of an optimization model for nano-grid operations, distinctly outlining the objectives: minimizing generation costs, equipment expenditures, and environmental impact. Our simulation results underscore the platform's ability to ensure stable nano-grid operations, facilitating effective energy management and optimization. To conclude, we've integrated data visualization using Node-red. This enables real-time monitoring and showcases the dynamic performance of each power generation unit within the nano-grid.

1. Introduction

The traditional power grid is struggling with energy instability, power security risks, and high energy consumption, whereas the nano-grid can offer sustainable energy supply and effective power management by fusing distributed energy, energy storage technology, and intelligent control equipment in a small-scale and localized manner. Involving numerous disciplines, including energy scheduling, energy management, optimization algorithms, etc., nano-grid research is now advancing quickly and offering fresh concepts and options for creating dependable and effective energy systems.

To achieve optimal energy utilization in the nano-grid, the power generating and energy storage systems from various sources must operate together in accordance with the needs of the load side. The focus of study has shifted to figuring out how to implement sensible scheduling and coordinated operation among solar power generation, wind power generation, diesel power generation, battery energy storage system, and external grid in response to the change in load value. In order to maximize energy efficiency and system dependability, optimization may involve the choice of sources, how power is distributed, how the energy storage system is charged and discharged, and other factors.

As traditional single-objective optimization methods are no longer able to meet practical needs, A multi-objective optimized energy mana-gement platform for Nano-grids based on Raspberry Pi is designed, achieving efficient energy distribution and management of Nano-grids. Raspberry Pi is used as the control platform, and the improved particle swarm optimization algorithm is introduced as the multi-objective optimization method, searching for the optimal solution by optimizing the position and velocity of particles. Meanwhile, joint simulation with the model built in Simulink and data visualization through Node-red are conducted, realizing real-time monitoring and displaying of the changes in various power generation units of Nano-grids, and achieving an efficient Nano-grids energy management system platform design.

2. Optimization Model for Nano-Grid System Operation

The Nano-grid system architecture, utilizing Raspberry Pi as the control platform, includes photovoltaic cells (PV), wind turbines (WT), diesel generators (DG), and battery energy storage system(BESS), referred with the Fig. 1. This Nano-grid operates in parallel with the external main grid with power exchange.

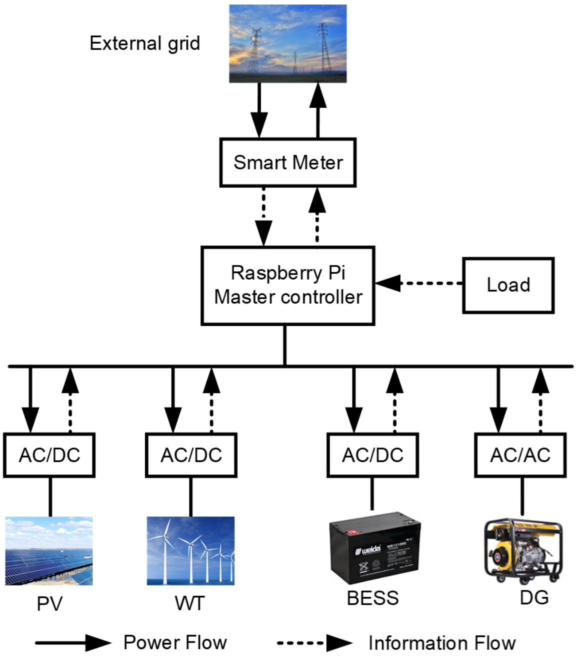

Fig. 1. Nano-grid System.

2.1 Photovoltaic Cell (PV) Model

Photovoltaic cells can convert solar energy into electrical energy, and their output power is mainly related to the intensity of sunlight, temperature, and the characteristics of the photovoltaic cells themselves. Photovoltaic cells generally operate in maximum power point tracking (MPPT) mode, whose output power model can be expressed as Eq. (1):

$$P_{\mathrm{pv}} = \eta_{\mathrm{pv}} A_{\mathrm{pv}} G(1-\tau)[1+\beta(T-T_{\mathrm{stc}})] \tag{1}$$

Among them, P_{pv} is the output power of photovoltaic cells; η_{pv} is the conversion efficiency of photovoltaic cells; A_{pv} is the area of photovoltaic panels; G is the ratio of light intensity to the light intensity under standard test conditions; τ is the light transmittance of photovoltaic cells; β is the temperature coefficient of the photovoltaic cell; T is the current operating temperature of photovoltaic cells; T_{stc} is the temperature under standard test conditions.

2.2 Wind Turbine (WT) Model

Wind turbines can convert wind energy into electrical energy, and their output power is mainly related to wind speed and the characteristics of the wind turbine itself, and the output power model is expressed as Eq. (2):

$$P_{\mathrm{WT}} = \begin{cases} 0 & 0 \le v \le v_{\mathrm{ci}} \\ P_{\mathrm{r}} \dfrac{v^3 - v_{\mathrm{ci}}^3}{{v_{\mathrm{r}}}^3 - v_{\mathrm{ci}}^3} & v_{\mathrm{ci}} \le v \le v_{\mathrm{r}} \\ P_{\mathrm{r}} & v_{\mathrm{r}} \le v \le v_{\mathrm{co}} \\ 0 & v_{\mathrm{co}} \le v \le v \end{cases} \tag{2}$$

where P_{WT} is the output power of the fan; P_{r} is the rated output power of the fan; V_{ci}, V_{r}, and V_{co} are respectively cut-in wind speed, rated wind speed and cut-out wind speed.

2.3 Diesel Generator (DG) Model

Diesel generators are commonly used as backup power sources or to provide stable power supply when renewable energy is not available. Their output power is related to multiple factors, including the characteristics of the diesel engine, load demand, and fuel supply, and the output power model is expressed as Eq. (3):

$$P_{\mathrm{DG}} = P_{\mathrm{rated}} \cdot [1 - k_1 \cdot (\frac{P_{\mathrm{rated}}}{P_{\mathrm{rated\_fuel}}})] \cdot [1 - k_2 \cdot (\frac{L}{L_{\mathrm{rated}}})] \tag{3}$$

Among them, P_{DE} is the output power of diesel generator; P_{rated} is the rated power of a diesel generator; $P_{\mathrm{rated\_fuel}}$ is the fuel consumption of a diesel engine under rated load. L is the load requirement of diesel engine; L_{rated} is the rated load of a diesel engine; k_1 is the fuel consumption coefficient of diesel engine, which is used to describe the relationship between generator output power and fuel consumption. k_2 is the load loss factor of a diesel engine and is used to describe the relationship between the output power of a generator and the load.

2.4 Battery Energy Storage System (BESS) Model

Battery energy storage systems are widely used in balancing grid loads, storing excess renewable energy, and responding to grid faults. The output power of batteries is not only related to parameters such as current, voltage, and capacity, but also to charging and discharging characteristics, battery chemical reactions, and environmental factors, and the output power model is expressed as Eq. (4):

$$SOC(t+1) = \begin{cases} SOC(t) + \eta_{\mathrm{ES}} \cdot [P_{\mathrm{all}}(t+1) - \dfrac{P_{\mathrm{load}}(t+1)}{\eta_{\mathrm{inv}}}] \cdot \Delta t \\ SOC(t) + \eta'_{\mathrm{ES}} \cdot [\dfrac{P_{\mathrm{load}}(t+1)}{\eta_{\mathrm{inv}}} - P_{\mathrm{all}}(t+1)] \cdot \Delta t \end{cases} \tag{4}$$

SOC(t+1) and *SOC*(t) are the capacity of the battery at time t+1 and time t respectively. η_{inv} is the working efficiency of the inverter; Respectively, η_{ES} and η'_{ES} are the charging and discharging efficiency of the battery; P_{all}(t+1) is the sum of output power of distributed power supply at t+1 time. P_{load}(t+1) is the total load of the system at time t+1.

3. Multi-Objective Optimization Model for Nano-Grids

3.1 Objective Function

Under the constraints of system requirements, a multi-objective optimization model is established for Nano-grids systems, taking into account the economic, reliability, and environmental aspects of

Nano-grids. The model aims to minimize the cost of electricity generation, equipment, and environmental pollution. Therefore, the definition of the objective function is as follows Eq. (5):

$$W = \alpha Y_1 + \beta Y_2 + \gamma Y_3 \tag{5}$$

Where W represents the total cost of Nano-grids, Y_1, Y_2, Y_3 represent the cost of electricity generation, equipment, and environmental pollution, respectively. α, β, and γ represent the proportion of electricity generation cost, equipment cost, and environmental pollution cost in the total cost of Nano-grids, and satisfy the condition that $\alpha + \beta + \gamma = 1$.

3.2 Power Generation Cost

The optimization goal in the grid-connected mode is to minimize the power generation cost of the microgrid.

$$Y_1 = \alpha \sum_{t=1}^{T} [C_{PV}(t) + C_{DE1}(t) + C_{BA1}(t) + C_{\mathrm{grid}}(t)] \tag{6}$$

$$\begin{cases} C_{\mathrm{PV}}(t) = P_{\mathrm{PV}}(t) \cdot C_{\mathrm{PV\_UNIT}} \\ C_{\mathrm{DE1}}(t) = P_{\mathrm{DE}}(t) \cdot C_{\mathrm{DE\_UNIT}} \\ C_{\mathrm{BA1}}(t) = P_{\mathrm{BA}}(t) \cdot C_{\mathrm{BA\_UNIT}} \\ C_{\mathrm{sell}}(t) = P_{\mathrm{sell}}(t) \cdot c_{\mathrm{sell}}(t) \\ C_{\mathrm{buy}}(t) = P_{\mathrm{buy}}(t) \cdot c_{\mathrm{buy}}(t) \\ C_{\mathrm{grid}}(t) = C_{\mathrm{sell}}(t) - C_{\mathrm{buy}}(t) \end{cases} \tag{7}$$

Among them, C_{PV}(t), C_{DE1}(t), C_{BA1}(t), and C_{gird}(t) are respectively the total cost of photovoltaic power generation at time t, the power generation cost of diesel engine, the power generation cost of battery energy storage system and the total cost of the interaction between the microgrid and the external main grid. $C_{\mathrm{PV\_UNIT}}$, $C_{\mathrm{DE\_UNIT}}$ and $C_{\mathrm{BA\_UNIT}}$ are respectively the unit cost of photovoltaic power generation, the unit cost of diesel generator and the unit cost of battery energy storage system. c_{buy}(t) and c_{sell}(t) are respectively the purchase price and sale price of microgrid and external main grid at time t. P_{PV}(t), P_{DE}(t) and P_{BA}(t) are respectively the power of photovoltaic power generation, the power of diesel generator and the power of battery energy storage system at time t; P_{buy}(t) and P_{sell}(t) are respectively the purchased power and sold power of microgrid and external main grid at time t.

3.3 Equipment Cost

The optimization goal in the grid-connected mode is to minimize the equipment cost of the microgrid.

$$Y_2 = \beta \sum_{t=1}^{T} [C_{\mathrm{DE2}}(t) + C_{\mathrm{BA2}}(t)] \tag{8}$$

$$\begin{cases} C_{\mathrm{DE2}}(t) = C_{\mathrm{DE\_OM}}(t) + C_{\mathrm{DE\_F}}(t) \\ C_{\mathrm{BA2}}(t) = C_{\mathrm{BA\_OM}}(t) \end{cases} \tag{9}$$

Among them, C_{DE2}(t) and C_{BA2}(t) are respectively the equipment cost of diesel generator and the equipment cost of battery energy storage system at time t. $C_{\mathrm{DE\_OM}}$(t) and $C_{\mathrm{DE\_F}}$(t) are respectively the operation and maintenance costs and fuel consumption costs of diesel generators at time t. $C_{\mathrm{BA\_OM}}$(t) is the operation and maintenance cost of the battery energy storage system at time t.

3.4 Environmental Pollution cost

The optimization goal in the grid-connected mode is to minimize the environmental pollution cost of microgrid.

$$Y_3 = \gamma \sum_{t=1}^{T} [C_{\mathrm{DE\_EN}}(t) + C_{\mathrm{grid\_EN}}(t)] \tag{10}$$

$$\begin{cases} C_{\mathrm{DE\_EN}}(t) = P_{\mathrm{DE}}(t) \cdot \sum_{k=1}^{n} (\zeta_1 \eta_{\mathrm{DE\_k}}) \\ C_{\mathrm{grid\_EN}}(t) = P_{\mathrm{buy}}(t) \cdot \sum_{k=1}^{n} (\zeta_2 \eta_{\mathrm{grid\_k}}) \end{cases} \tag{11}$$

Where, $C_{\mathrm{DE\_EN}}$(t) and $C_{\mathrm{grid\_EN}}$(t) are the environmental pollution cost of diesel generator and the environmental pollution treatment cost of external main grid at time t respectively. ζ_1 and ζ_2 are the cost coefficients of diesel generator treating certain pollutants. $\eta_{\mathrm{DE\_k}}$ and $\eta_{\mathrm{grid\_k}}$ are the emissions of certain pollutants described by the operation of diesel generators and the emissions of certain pollutants generated by the operation of the external main grid, respectively.

3.5 Constraint Conditions

a. Power Balance Constraint:

$$P_{\mathrm{PV}}(t) + P_{\mathrm{WT}}(t) + P_{\mathrm{DE}}(t) + P_{\mathrm{BA}}(t) + P_{\mathrm{grid}}(t) = P_{\mathrm{Load}}(t) \tag{12}$$

b. Battery operation constraints:

$$\begin{cases} P_{\mathrm{BA\_min}}(t) \le P_{\mathrm{BA}}(t) \le P_{\mathrm{BA\_max}}(t) \\ SOC_{\mathrm{min}}(t) \le SOC(t) \le SOC_{\mathrm{max}}(t) \end{cases} \tag{13}$$

PBA_min(t) and PBA_max(t) are the minimum and maximum charging and discharging power of the battery energy storage system respectively. SOCmin(t) and SOCmax(t) are the minimum and maximum capacities of the battery energy storage system respectively.

c. Diesel power generation operation constraint:

$$P_{\mathrm{DE\_min}}(t) \le P_{DE}(t) \le P_{\mathrm{DE\_max}}(t) \tag{14}$$

$P_{\mathrm{DE\_min}}$(t) and $P_{\mathrm{DE\_max}}$(t) are the minimum and maximum power of diesel generators respectively.

d. Transmission power constraints of microgrid contact lines:

$$P_{\mathrm{grid\_min}}(t) \le P_{\mathrm{grid}}(t) \le P_{\mathrm{grid\_max}}(t) \tag{15}$$

$P_{\mathrm{grid\_min}}$(t) and $P_{\mathrm{grid\_max}}$(t) are respectively the upper limit and lower limit of the transmission power of the microgrid connection line.

3.6 Improved Particle Swarm Optimization Algorithm

Adaptive inertia weight is an improvement strategy in the Particle Swarm Optimization (PSO) algorithm that enhances the algorithm's search capability, accelerates convergence speed, improves algorithm robustness, and achieves a balance between exploration and exploitation, thereby effectively finding the optimal solution to optimization problems. The formulas are as follows Eq. (16):

$$\begin{cases} x_{\mathrm{i}}^{d+1} = x_{\mathrm{i}}^{d} + v_{\mathrm{i}}^{d} \\ v_{\mathrm{i}}^{d} = w v_{\mathrm{i}}^{d-1} + c_1 r_1 (p_{\mathrm{best\_i}}^{d} - x_{\mathrm{i}}^{d}) + c_2 r_2 (g_{\mathrm{best\_i}}^{d} - x_{\mathrm{i}}^{d}) \\ w = w_{\max} - [(w_{\max} - w_{\min}) \cdot i] / i_{\max} \end{cases} \tag{16}$$

where $x_{\mathrm{i}}^{\mathrm{d}}$ and $v_{\mathrm{i}}^{\mathrm{d}}$ are the current position and current velocity of the particle, respectively; $x_{\mathrm{i}}^{\mathrm{d+1}}$ is the next position of the particle; $v_{\mathrm{i}}^{\mathrm{d-1}}$ is the previous moment velocity of a particle; w is the inertia weight; $p_{\mathrm{best\_i}}^{\mathrm{d}}$ and $g_{\mathrm{best\_i}}^{\mathrm{d}}$ are individual local extrema and global optimal extremum, respectively; c_1 and c_2 are individual learning factors and social learning factors, respectively; r_1 and r_2 are random numbers evenly distributed between 0 and 1, respectively. $\mathrm{w}_{\mathrm{max}}$ and $\mathrm{w}_{\mathrm{min}}$ are the maximum and minimum values of the initial weight, respectively; i and $\mathrm{i}_{\mathrm{max}}$ are the number of iterations and the total number of iterations, respectively.

4. Design of an Energy Management Platform Based on Raspberry PI

4.1 The Multi-Objective Nano-grid Optimization Process

The multi-objective optimization process of Nano-grid is divided into two parts, namely the PSO algorithm process and the overall process. The PSO algorithm flow is referred with the Fig. 2, and the overall flow is referred with the Fig. 3.

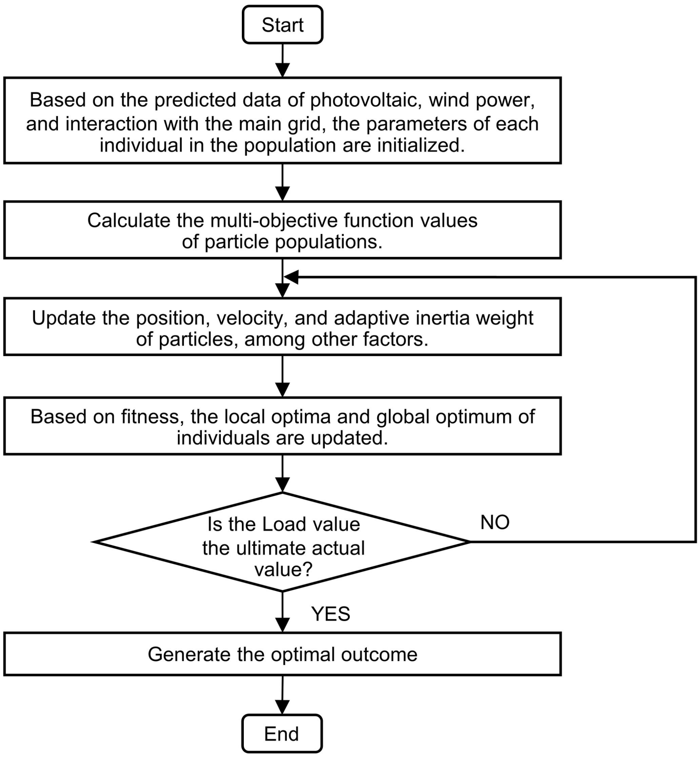

Fig. 2. PSO Algorithm Flow.

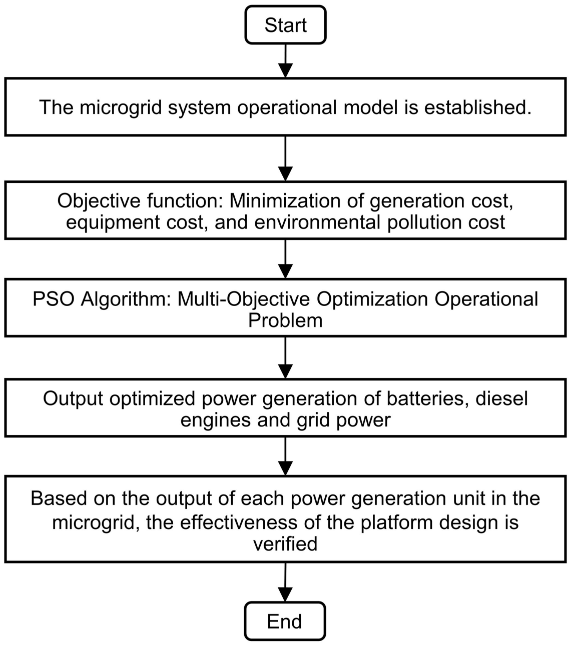

Fig. 3. Overall Flow.

4.2 Simulation of Multi-objective Optimization Energy Management Platform for Nano-grid

Using Python on the Raspberry Pi, a human-machine interface can be developed to input load values. Depending on the actual situation, the load value can be customized by the user, and in this case, the Load value is set to 11.2 kW.

As shown in the Fig. 4, the Simulink model imports forecast data for PV, wind, and grid power through the Signal Builder module for simulation, converts the data format through the signal_to_byte module, and then sends the data to the Raspberry Pi via the TCP/IP Send module.

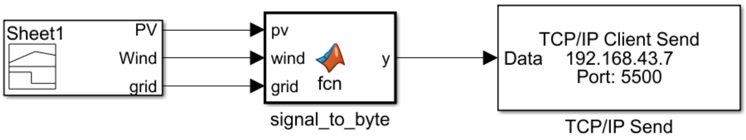

Fig. 4. TCP/IP Data Transmission

As shown in Fig. 5, the Raspberry Pi transfers the power from the optimized battery and diesel engine to the Simulink terminal via TCP/IP, changes the data format, and then transforms the power into the appropriate voltage for two controlled voltage sources that represent the real-world scenario.

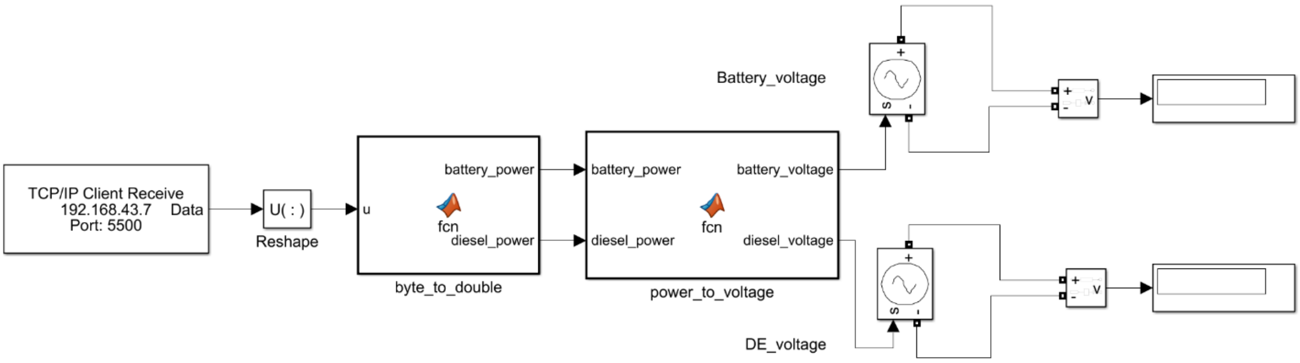

Fig. 5. TCP/IP Data Reception and Control.

Fig. 6 displays the outcomes of the co-simulation between Simulink and the Raspberry Pi. The polylines referred with the Fig. 6 represent PV, Wind, BESS, DE, and Grid Power.

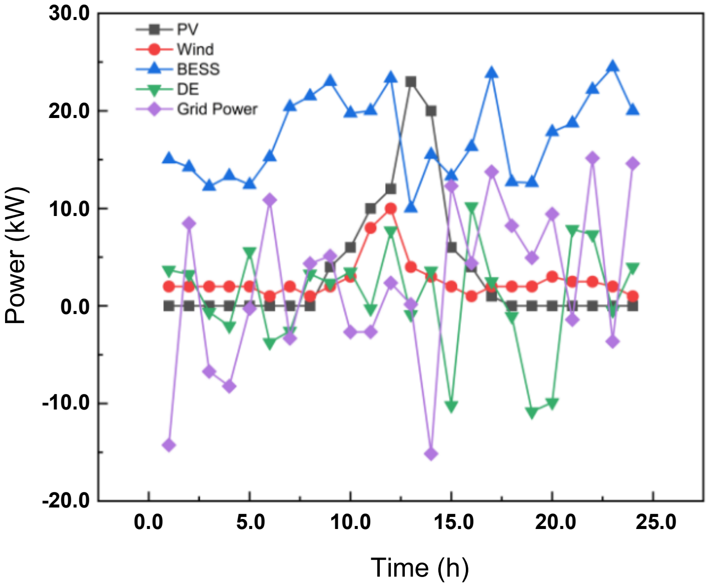

Fig. 6. Operation Power of Each Microgrid Device

The output power of the battery energy storage system and diesel engine of the microgrid can be simulated in different time periods and under different conditions to meet the power supply needs of the microgrid in accordance with the load side, provided that the multi-objective optimization is met with the lowest cost of power generation, the smallest equipment cost, and the lowest cost of environmental pollution.

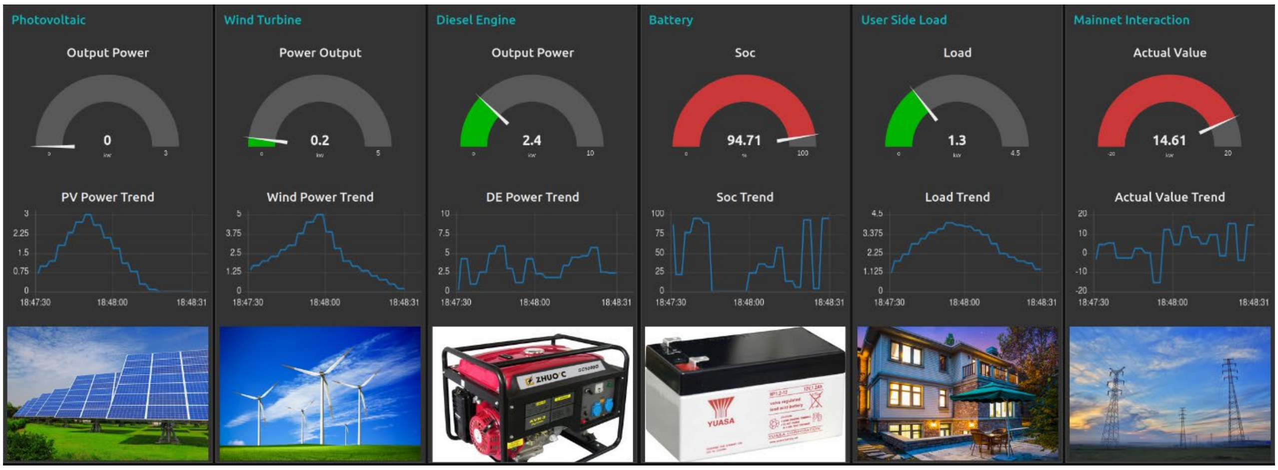

Fig. 7. Node-red Data Visualization.

Fig. 7 depicts the layout of a multi-objective, Raspberry Pi-based energy management platform for microgrids. The power value of the optimized battery energy storage system and the diesel engine is received and given to two controlled voltage sources that simulate the actual situation, and the change trend of the operating power of each piece of equipment in the microgrid can be tracked in real time on the node-red platform of the Raspberry Pi by simulating photovoltaic power generation, wind power generation, and main grid power in the Simulink model. The physical platform is shown in Fig. 8.

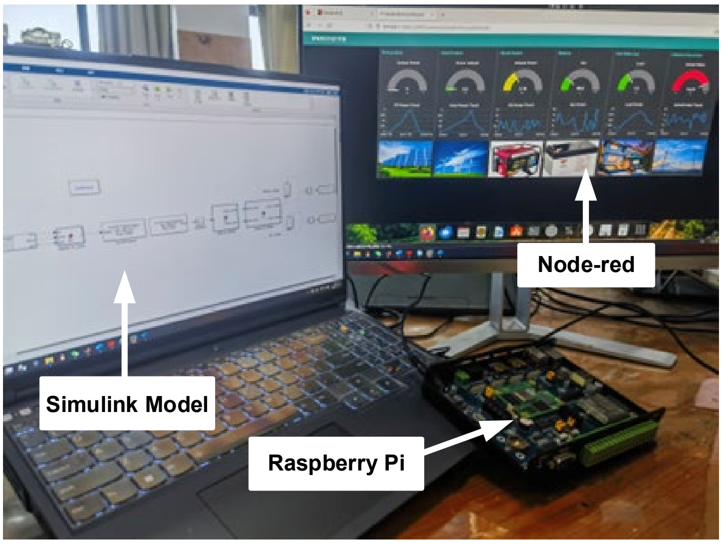

Fig. 8. Physical Platform

5. Conclusion

A multi-objective optimization energy management platform for Nano-grids based on Raspberry Pi is presented, which employs a joint simulation approach to using Simulink and Raspberry Pi to effectively simulate the operation of Nano-grids. Through TCP/IP data communication, the PSO algorithm implemented on Raspberry Pi achieves multi-objective optimization of Nano-grids, such as reducing generation costs, operating costs, and environmental pollution costs, while also enabling real-time monitoring and display of the output power trend of each generation unit in the Nano-grids through Node-red. Simulation results demonstrate that this design platform can effectively manage and optimize energy while ensuring stable operation of Nano-grids by simulating their operation.

For more rigorous and complex environments, the stable and efficient operation of the EMS platform will be the direction of my further research.

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