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Research on the Flexibility Margin of an Electric–Hydrogen Coupling Energy Block Based on Model Predictive Control

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Hydrogen energy plays an important role in the transformation of low-carbon energy, and electric–hydrogen coupling will become a typical energy scenario. Aiming at the operation flexibility of a low-carbon electricity–hydrogen coupling system with high proportion of wind power and photovoltaic, this work studies the flexibility margin of an electricity–hydrogen coupling energy block based on model predictive control. By analyzing the power exchange characteristics of heterogeneous energy, the homogenization models of various heterogeneous energy sources are established. According to the analysis of power system flexibility margin, three dimensions of flexibility margin evaluation indexes are defined from the dimension of system operation, and an electricity–hydrogen coupling energy block scheduling model is established. The model predictive control algorithm is used to optimize the power balance operation of the electro–hydrogen coupling energy block, and the flexibility margin of the energy block is quantitatively analyzed and calculated. Through the example analysis, it is verified that the calculation method proposed in this article can not only realize the online power balance optimization of the electric–hydrogen coupling energy block but also effectively quantify the operation flexibility margin of the electric–hydrogen coupling energy block.

Keywords: MPC, electro–hydrogen coupling, homogenization modeling, power balance, flexibility margin

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INTRODUCTION

As the penetration ratio of renewable energy increases year by year, there is a reverse change between supply and demand of power system flexibility, and the phenomenon of renewable energy power limitation is increasing day by day (Mahesh and Singh Sandhu, 2015; Li et al., 2022a). This transition not only undoubtedly brings huge economic and environmental benefits but also brings huge challenges to the secure and stable operation of today's power system because of the uncertainties of renewable power generations (Li et al., 2021a; Li et al., 2022b; Shi et al., 2022). As a clean secondary energy (Pan et al., 2020), it is particularly important for hydrogen to completely call all links of source charge storage to participate in flexibility adjustment and balance through an electric–hydrogen coupling power generation system and cooperate with the consumption of renewable energy (Shao et al., 2021; Zhu et al., 2022). Power to gas (P2G), as links of multi-energy carriers, has been successfully adopted to strengthen the coupling of different energy systems (Li et al., 2021b).

Hydrogen–electric coupling will greatly contribute to promote renewable energy consumption and build a low-carbon sustainable modern energy system (Xiaochen et al., 2021; Wang et al., 2022). To solve the problems of large differences in heterogeneous energy models and difficult flexibility margin analysis in an electro–hydrogen coupling module, it is important to build an effective electric–hydrogen coupling contract qualitative energy module and carry out flexibility margin calculations.

At present, many experts and scholars around the world have carried out research on the modeling and flexibility margin analysis of an electro–hydrogen coupling module. Khan and Iqbal (2009) established a linear model of a wind hydrogen hybrid energy system based on empirical and physical relations and analyzed the performance of a hybrid energy system through digital simulation. Fakehi et al. (2015) carried out the conceptual modeling of the hybrid renewable energy system based on a wind energy/electrolyzer/proton exchange membrane fuel cell. At the same time, based on the thermodynamic, electrochemical, and mechanical models of different components of the hybrid system, the energy analysis framework of the hybrid system was established. Also, the model was used for simulation analysis to calculate the influence of different operating parameters on energy application efficiency. Sharma and Sathans (2015) established a renewable energy hybrid system model composed of photovoltaic cells, wind turbines, battery energy storage systems, and diesel power generation systems. Three cases are set to analyze the impact of system performance and intermittent renewable energy on the system. In addition, in the operation and analysis of the multi-energy power system, research institutions at home and abroad have carried out relevant research on the flexibility evaluation of two or a few energy resource systems. Starting from the dimension of flexibility planning, Ma et al. (2012) defined power system flexibility as the ability of the system to allocate its resources when the system network or load changes and took this flexibility as one of the indicators to evaluate whether the planning scheme is reasonable. The flexibility of the power system described in the literature (Adams et al., 2010) is the ability to quickly adapt and restore stability when the system undergoes unpredictable fluctuations or changes under certain economic constraints. Agency (2009) qualitatively described the system flexibility in this area by using the switching capacity of hydropower and thermal power generation, and the economic benefits brought by hydrothermal power switching can measure the advantages and disadvantages of switching schemes under different operating states. Meibom et al. (2007) and Lannoye et al. (2012) define the unit flexibility index and system flexibility index according to the unit flexibility parameters and establish the unit combination model considering the unit expansion with the goal of minimizing the total cost.

The aforementioned literature lacks homogeneous equivalent modeling of heterogeneous energy systems and a multi-dimensional quantitative understanding of flexibility. Moreover, the flexibility evaluation index is one-sided and single, and it is difficult for the flexibility evaluation to reveal the flexibility boundary of the system operation. Therefore, this study analyzes the power characteristics of the heterogeneous energy of electricity and hydrogen, and carries out the homogeneity modeling of the heterogeneous energy. From the three dimensions of climbing, power, and energy, the energy block balance criterion and flexibility margin index of electric-hydrogen coupling are proposed. The flexibility margin of the electric-hydrogen coupling energy block was analyzed, and the power balance optimization calculation method of the energy block based on model predictive control (MPC) was proposed. Finally, combined with the historical data of a new energy demonstration area in my country, the calculation method of the flexibility margin of the electricity-hydrogen coupling energy block proposed in study paper was verified.

ELECTRO–HYDROGEN COUPLING ENERGY BLOCK AND HOMOGENIZATION MODELING

Based on the existing gas turbine, wind power, and photovoltaic structures, combined with the characteristics of an electrolytic cell and fuel cell, an electric- hydrogen coupling energy block was constructed, as shown in **Supplementary Figure S1**.

It can be seen from **Supplementary Figure S1** that in the energy block composed of a variety of heterogeneous energy sources, wind power, photovoltaic, and gas units were coupled with hydrogen energy storage devices. At the same time, the balance supply of electric load and hydrogen load was realized through internal energy regulation. The mutual conversion between hydrogen energy and electric energy was the medium connecting various heterogeneous energy models in the electric-hydrogen coupling energy block. For the outside of the electric-hydrogen coupling energy block, the energy module was supplied by wind energy, solar energy, gas, and hydrogen, and the supply and demand balance of source load was met through internal energy conversion. For the inside of the electric- hydrogen coupling energy block, wind airports and photovoltaic stations convert the supplied energy into electric energy. When the power output was higher than the electric load demand, the electrolytic cell absorbed the excess power of the system, converted the electric energy into hydrogen energy and stored it. When the power output is less than the electric load demand, the fuel cell will supplement the missing power. The hydrogen storage capacity is determined by the electric load and hydrogen load. The battery energy storage can balance the climbing power and make up for the power shortage.

The electro–hydrogen coupling energy block involves a variety of heterogeneous energy units with different physical media and technical characteristics. For its complex parameters and boundary conditions, it is important to establish a unified model for analysis.

Combined with the structure of the electro–hydrogen coupling energy block and considering the power exchange characteristics of heterogeneous energy, the model framework is shown in **Supplementary Figure S2**.

As can be seen from the figure, the supply and demand side of the model includes the energy supply process ($\zeta_i > 0$), demand process ($\zeta_i < 0$), and spillover energy ($w_i \geq 0$). The model system side includes the homogenization model and the conversion and transmission process of electric energy and hydrogen energy. By changing the model parameters, the model can characterize the elements in the energy block.

The model set is $i \in \{w, pv, b, h, f, \cdots\}$, where w represents wind farm, pv represents photovoltaic station, b represents battery energy storage, h represents hydrogen energy storage system, and f represents gas unit. The general formula of model i is

$$C_i dx_i = \eta_{ex,i}\xi_i - \eta_{gen,i} p_{gen,i}\Delta t + \eta_{load,i} p_{load,i}\Delta t - w_i, \tag{1}$$

where C_i is the energy storage capacity, dx_i is the change in state of charge (SOC) of energy storage, $\eta_{\text{gen},i}$ is the output efficiency, $p_{\text{gen},i}$ is the output power, η_{load} is the load efficiency, $p_{load,i}$ is the load power, $\eta_{\text{ex},i}$ is the conversion efficiency of external energy, ζ_i is the output/consumption of external energy, w_i is the overflow energy, and Δt is the dispatching cycle of energy storage.

According to the existence of energy storage, the heterogeneous energy models in the energy module are divided into two categories. The renewable energy power generation model without energy storage ($C_i dx_i = 0$) is as follows:

The wind farm model is formulated by

$$C_w dx_w = 0 = \xi_w - \eta_{gen,w} p_{gen,w}\Delta t - w_w, \tag{2}$$

where ζ_w is the wind energy collected by the wind farm for the collection and calculation of wind speed data, $\eta_{gen,w}$ is the power generation efficiency of the wind farm itself, $p_{gen,w}$ is the output power of the wind farm, and w_w is the waste air volume in the dispatching cycle.

The PV station model is given as follows:

$$C_{pv} dx_{pv} = 0 = \xi_{pv} - \eta_{gen,pv} p_{gen,pv}\Delta t - w_{pv}, \tag{3}$$

where ζ_{pv} is the solar energy collected by the photovoltaic station for the collection and calculation of irradiation data, $\eta_{gen,pv}$ is the power generation efficiency of the photovoltaic power plant itself, $p_{gen,pv}$ is the output power of the photovoltaic station, and w_{pv} is the light rejection in the dispatching cycle.

The heterogeneous energy model with energy storage ($C_i dx_i \neq 0$) can be depicted in the following section.

The battery energy storage model is

$$C_b dx_b = \eta_{load,b} p_{load,b}\Delta t - \eta_{gen,b} p_{gen,b}\Delta t, \tag{4}$$

where C_b represents the energy storage capacity of the battery, $\eta_{load,b}$ represents the charging efficiency of the battery, $p_{gen,b}$ represents the charging power of the battery, $\eta_{gen,b}$ represents the discharge efficiency of the battery, and $p_{gen,b}$ represents the discharge power of the battery.

The hydrogen energy storage system model is calculated as

$$C_h dx_h = \xi_h + \eta_{load,h} p_{load,h}\Delta t - \eta_{gen,h} p_{gen,h}\Delta t, \tag{5}$$

where C_h represents the capacity of the hydrogen storage tank, ζ_h represents the hydrogen supply and demand, when $\zeta_h > 0$, it represents the hydrogen supply, when $\zeta_h < 0$, it represents the hydrogen demand, $\eta_{load,h}$ represents the hydrogen production efficiency of the electrolytic cell, $p_{load,h}$ represents the power of the electrolytic cell, $\eta_{gen,h}$ represents the power generation efficiency of the fuel cell, and $p_{gen,h}$ represents the output power of the fuel cell.

The gas unit model is given as follows:

$$C_f dx_f = \xi_f - \eta_{gen,f} p_{gen,f}\Delta t, \tag{6}$$

where C_f represents the capacity of the gas storage pipe, ζ_f is the gas input, $\eta_{gen,f}$ is the gas power generation efficiency, and $p_{gen,f}$ is the output power of the gas unit.

The constraints to be met by the model are as follows:

1) Climbing constraint: unit and load climbing rate constraint:

$$dp_{load.i.\min} \leq dp_{load,i} \leq dp_{load,i,\max}, \tag{7}$$

where $dp_{load,i,\min}$ and $dp_{load,i,\max}$ are the lower limit and upper limit of the load climbing rate, respectively.

$$dp_{gen,i,\min} \leq dp_{gen,i} \leq dp_{gen,i,\max}, \tag{8}$$

where $dp_{gen,i,\min}$ and $dp_{gen,i,\max}$ are the lower limit and upper limit of unit climbing rate, respectively.

2) Output power constraints: system load and output constraints:

$$0 \leq kp_{load,i,\min} \leq kp_{load,i} \leq kp_{load,i,\max}, \tag{9}$$

where $p_{load,i,\min}$ and $p_{load,i,\max}$ are, respectively, the upper and lower limit values of load demand, and each efficiency parameter is a variable, which changes with the change of input/output power, where $\eta_{gen,i} = f(p_{gen,i})$, $\eta_{load,i} = f(p_{load,i})$, $\eta_{ex,i} = f(\zeta_i)$, k is a binary variable. Here, $k = 1$ or 0 represents if the load is running or not running, respectively.

$$0 \leq Xp_{gen,i,\min} \leq Xp_{gen,i} \leq Xp_{gen,i,\max}, \tag{10}$$

where $p_{gen,i,\min}$ and $p_{gen,i,\max}$ are, respectively, the upper limit and lower limit of unit output, and each efficiency parameter is a variable, which changes with the change of input/output power, where $\eta_{gen,i} = f(p_{gen,i})$, $\eta_{load,i} = f(p_{load,i})$, $\eta_{ex,i} = f(\zeta_i)$, X is a binary variable. Here, $X = 1$ or 0 represents a unit that is running or not running, respectively.

3) Energy storage constraints: state of charge and energy storage capacity constraints:

$$\begin{cases} C_i > 0, \ x_{\min} \leq x_i \leq x_{\max} \\ C_i = 0 \end{cases}, \tag{11}$$

where $x_{\min}$ and $x_{\max}$ are the upper and lower limits of the state of charge, respectively. When there is energy storage, $C > 0$, otherwise, when $C = 0$, there is no state of charge constraint.

4) Renewable energy abandonment constraints: energy input/consumption and spillover energy constraints:

$$\begin{cases} \zeta_i > 0, w_i \geq 0, \zeta_i - w_i \geq 0 \\ \zeta_i < 0 \end{cases}, \tag{12}$$

where $\zeta_i > 0$ represents the external input of energy, $w_i \geq 0$ represents the existence of overflow energy (wind and light abandonment), and $\zeta_i < 0$ represents the external consumption of energy.

FLEXBILITY MARGIN ANALYSIS AND EVALUATION INDEX OF THE ENERGY BLOCK

Energy Block Flexibility Margin Analysis

The flexibility demand of the energy block mainly comes from the intermittence and fluctuation of the load and renewable energy, and has certain directionality. Flexibility can be divided into upward flexibility requirements and downward flexibility requirements. When the system has an upward flexibility demand (p_{net}≤0), the flexibility resource response is gas unit, battery energy storage and discharge, fuel cell, and load rejection. When the system has a downward flexibility demand (p_{net}≥0), the flexibility resource response is battery energy storage charging, electrolytic cell, and renewable energy abandonment.

Aiming at the balance between the supply and demand of flexibility in an electro–hydrogen coupling energy block, this study will analyze flexibility from three dimensions: climbing power, output power, and power supply (Dingyao et al., 2014; Dingyao et al., 2015; Li et al., 2020).

As shown in **Supplementary Figure S3**, four operation points were set to analyze the flexibility margin of the system at t_2 time. Operation points A and B have downward flexibility requirements, and the flexibility provided at t_1 time is r_p^-, p_p^-, e_p, while the downward flexibility required by operation point A is r_n^-, p_n^-, e_n^-. It can be seen from the figure that the flexibility margin required for the operation point A is outside the system flexibility margin envelope, r_p^-, p_p^-, e_p^- < r_n^-, p_n^-, e_n^- and the system cannot meet the flexibility requirements of the operation point A. The flexibility margin required by the operation point B is within the system flexibility margin envelope, and the system can meet the flexibility margin requirements of the operation point B.

Operation points C and D have upward flexibility requirements. The operation point C is within the flexibility margin envelope, which can meet the requirements of the flexibility margin. The operation point D is outside the envelope of flexibility margin, r_p^+, p_p^+, e_p^+>r_n^+, p_n^+, e_n^+, which cannot meet the requirements of the flexibility margin.

The flexibility balance criterion of the electric–hydrogen coupling energy block is

$$\begin{cases} \sum\limits_i r^+_{p,i,t} \geq r^+_{n,t}, \sum\limits_i r^-_{p,i,t} \leq r^-_{n,t} \\ \sum\limits_i p^+_{p,i,t} \geq p^+_{n,t}, \sum\limits_i p^-_{p,i,t} \leq p^-_{n,t} \\ \sum\limits_i e^+_{p,i,t} \geq e^+_{n,t}, \sum\limits_i e^-_{p,i,t} \leq e^-_{n,t} \end{cases}, \tag{13}$$

where $r^+_{p,i,t}$ and $r^-_{p,i,t}$ are the uphill power and downhill power, respectively, provided by unit i at time t, $r_{n,t}$ is the uphill power required by the system at time t, $p^+_{p,i,t}$ and $p^-_{p,i,t}$ are the up output power and down output power, respectively, provided by unit i at time t, $p_{n,t}$ is the output power required by the system at time t, $e^+_{p,i,t}$ and $e^-_{p,i,t}$ are the upper power supply and lower power supply, respectively, provided by unit i at time t, and $e_{n,t}$ is the power supply required by the system at time t.

Energy Block Evaluation Index

The flexibility margin required at each running time and the upper and lower limits of the flexibility margin provided by the energy block were calculated, the flexibility margin envelope was drawn, and the boundary of the system flexibility margin was analyzed (Ulbig and Andersson, 2015; Ji et al., 2019). Through the analysis of the flexibility margin required by the operation point, the expectation of an insufficient flexibility margin in each dimension is defined as an index to measure the flexibility margin of the energy block.

To enable it to effectively reflect the system's ability to respond to changes in net load, the indicators are as follows:

1) The climbing power does not meet the index E_{IR}, which indicates the expected value of the difference between the up/down climbing power provided by the system and the actual demand climbing power within the operation day.

$$E_{IR} = \rho_s \left(\sum_{t=1}^{N_L} \left| dP_{net,t} - \sum_{i=1}^{N_G} dP_{gen,i} \right| + \left| \sum_{i=1}^{N_L} dP_{load,i} - dP_{net,t} \right| \right). \tag{14}$$

In **formula (14)**,

$$\rho_s = \frac{\beta_{s,t}}{N_T}, \tag{15}$$

where $dP_{net,t}$ represents the net load climbing rate at time t, ρ_s represents the probability of an insufficient flexibility margin in scenario s, N_T represents the number of system dispatching intervals, $\beta_{s,t}$ represents the number of insufficient flexibility margins, N_G represents the number of generator units, and N_L represents the number of loads.

2) The output power does not meet the index E_{IO}, which indicates the expected value of the difference between the up/down power provided by the system and the actual demand power within the operation day.

$$E_{IO} = \rho_s \left(\sum_{t=1}^{N_T} \left| P_{net,t} - \sum_{i=1}^{N_G} P_{gen,i} \right| + \left| \sum_{i=1}^{N_L} P_{load,i} - P_{net,t} \right| \right), \tag{16}$$

where $P_{net,t}$ represents the net load power at time t.

3) The provided electric energy does not meet the E_{IC} index, which indicates the expected value of the difference between the up/downregulated electric energy provided by the system energy storage unit and the actual demand electric energy within the operation day.

$$E_{IC} = \rho_s\left(\sum_{t=1}^{N_T}\left|\int_t^{t+1} P_{net,t}dt - \sum_{i=1}^{N_G}\int_t^{t+1} P_{gen,i}dt\right| + \left|\sum_{i=1}^{N_L}\int_t^{t+1} P_{load,i}dt - \int_t^{t+1} P_{net,t}dt\right|\right). \quad (17)$$

The abovementioned three indicators show the expectation of an insufficient flexibility margin as that the flexibility margin unit cannot meet the change of system static load.

ONLINE SOLUTION OF ENERGY BLOCK FLEXIBILITY MARGIN BASED ON MODEL PREDICTIVE CONTROL

The state space of a linear discrete system is expressed as

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + Dd(k) \\ y(k) = Cx(k) \end{cases}, \quad (18)$$

where x is the state variable, u is the control variable, d is the disturbance variable, y is the controlled output, A, B, and C are the system matrix, control matrix, and disturbance matrix, respectively, C is the output matrix, k is the current time, and k+1 is the next time.

Bringing **eqs 2–6** into **eq 18**, the specific form of state space expression is

$$\begin{cases} x_w(k+1) = \zeta_w(k) - \eta_{gen,w}p_{gen,w}(k)\Delta t - w_w(k) \\ x_{pv}(k+1) = \zeta_{pv}(k) - \eta_{gen,pv}p_{gen,pv}(k)\Delta t - w_{pv}(k) \\ x_b(k+1) = x_b(k) + \dfrac{1}{C_b}\left(\eta_{load,b}p_{load,b}(k)\Delta t - \eta_{gen,b}p_{gen,b}(k)\Delta t\right) \\ x_h(k+1) = x_h(k) + \dfrac{1}{C_h}\left(\zeta_h(k) + \eta_{load,h}p_{load,h}(k)\Delta t - \eta_{gen,h}p_{gen,h}(k)\Delta t\right) \\ x_f(k+1) = x_f(k) + \zeta_f(k) - \eta_{gen,f}p_{gen,f}(k). \end{cases} \quad (19)$$

The vector formed by the energy storage SOC is selected as the state variable, namely,

$$x(k) = \left[x_w(k), x_{pv}(k), x_e(k), x_h(k), x_f(k)\right]^T. \quad (20)$$

The vector composed of the output, load power, and overflow energy of each unit is taken as the control variable, namely,

$$u(k) = \left[p_{gen,w}(k), p_{gen,pv}(k), p_{gen,b}(k), p_{load,b}(k), p_{gen,h}(k), p_{load,h}(k), p_{gen,f}(k), w_w(k), w_{pv}(k)\right]^T. \quad (21)$$

We take wind power, photovoltaic, hydrogen, and coal energy supply vectors as disturbance variables, namely,

$$d(k) = \left[\xi_w(k), \xi_{pv}(k), \xi_h(k), \xi_f(k)\right]^T. \quad (22)$$

We take the vector composed of battery energy storage and hydrogen energy storage SOC as the output variable, namely,

$$y(k) = \left[x_b(k), x_h(k)\right]^T. \quad (23)$$

The system matrix, control matrix, output matrix, and disturbance matrix of the energy module are, respectively,

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (24)$$

$$B^T = \begin{bmatrix} -\eta_{gen,w} & 0 & 0 & 0 & 0 \\ 0 & -\eta_{gen,pv} & 0 & 0 & 0 \\ 0 & 0 & \dfrac{-\eta_{gen,b}\Delta t}{C_b} & 0 & 0 \\ 0 & 0 & \dfrac{\eta_{load,e}\Delta t}{C_e} & 0 & 0 \\ 0 & 0 & 0 & \dfrac{-\eta_{gen,h}\Delta t}{C_h} & 0 \\ 0 & 0 & 0 & \dfrac{\eta_{load,h}\Delta t}{C_h} & 0 \\ 0 & 0 & 0 & 0 & -\eta_{gen,f} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \quad (25)$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad (26)$$

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (27)$$

The error between the estimated output value of spilled energy and stored energy SOC and the daily planned value was the smallest, and the control active power regulation increment of each unit was the smallest. The objective function of the electro–hydrogen coupling energy block is

$$\min J(k) = \sum_{j=1}^{N_p}\left\|y(k+j) - y_{ref}(k+j)\right\|_Q^2 + \sum_{j=0}^{N_c}\left\|\Delta u(k+j)\right\|_R^2, \quad (28)$$

where y_{ref} is the reference trajectory of state quantity, Q and R are the error and input weighting matrix, respectively, and N_p and N_c are, respectively, the prediction time domain and control time domain.

The constraints are as follows:

$$\mathrm{S\cdot t\cdot}\sum_{i=1}^{N_G} p_{gen,i} - \sum_{i=1}^{N_L} p_{load,i} - P_{load}^t = 0, \quad (29)$$

$$\Delta u_{\min} \le \Delta u \le \Delta u_{\max}, \quad (30)$$

$$u_{\min} \le u \le u_{\max}, \quad (31)$$

$$x_{\min} \le x \le x_{\max}, \quad (32)$$

where P_{load}^{t} represents the system load demand power at time t.

Vector $E(k)$ is defined as the deviation between the system free response and the future target trajectory:

$$E(k) = Y_{ref}(k) - M_{x_1}x(k) - M_{u_1}u(k-1). \tag{33}$$

In **formula (33)**,

$$M_{x_1} = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_c} \\ CA^{N_c+1} \\ \vdots \\ CA^{N_p} \end{bmatrix} M_{u_1} = \begin{bmatrix} CB \\ CAB+CB \\ \vdots \\ \sum_{i=0}^{N_c-1} CA^iB \\ \sum_{i=0}^{N_c} CA^iB \\ \vdots \\ \sum_{i=0}^{N_p-1} CA^iB \end{bmatrix}, \tag{34}$$

where for matrices A, B, and C are as in **Eqs 24–26**; **Eq 33** is substituted into **Eq 28** to obtain

$$\begin{aligned} J_k &= \left\|Y(k) - Y_{ref}(k)\right\|_Q^2 + \|\Delta U(k)\|_R^2, \\ &= \left\|M_{\Delta u_1}\Delta U(k) - E(k)\right\|_Q^2 + \|\Delta U(k)\|_R^2, \\ &= \Delta U^T(k)\left[M_{\Delta u_1}^T Q M_{\Delta u_1} + R\right]\Delta U(k) \\ &\quad -2E^T(k)QM_{\Delta u_1}\Delta U(k) + E^T(k)QE(k). \end{aligned} \tag{35}$$

The abovementioned formula is written as the standard form of secondary planning:

$$J_k = \frac{1}{2}\Delta U^T(k)H(k)\Delta U(k) + f^T\Delta U(k). \tag{36}$$

In **formula (36)**,

$$\begin{aligned} H &= 2\left(M_{\Delta u_1}^T Q M_{\Delta u_1} + R\right), \\ f &= -2\left(M_{\Delta u_1}^T QE(k)\right), \end{aligned} \tag{37}$$

$$M_{\Delta u_1} = \begin{bmatrix} CB & \cdots & 0 \\ CAB+CB & \cdots & 0 \\ \vdots & \ddots & \vdots \\ \sum_{i=0}^{N_c-1} CA^iB & \cdots & B \\ \sum_{i=0}^{N_c} CA^iB & \cdots & CAB+CB \\ \vdots & \vdots & \vdots \\ \sum_{i=0}^{N_p-1} CA^iB & \cdots & \sum_{i=0}^{N_p-N_c} CA^iB \end{bmatrix}. \tag{38}$$

The constraint condition of **Eq 36** is

$$\tilde{A}\Delta U(k) \le \tilde{b}. \tag{39}$$

In **formula (39)**,

$$\tilde{A} = \begin{bmatrix} \Pi & -\Pi & \Lambda & -\Lambda & M_{\Delta u_2} & -M_{\Delta u_2} \end{bmatrix}^T, \tag{40}$$

$$\tilde{b} = \begin{bmatrix} \Delta U_{\max} \\ -\Delta U_{\min} \\ U_{\max} - \Psi u(k-1) \\ -U_{\min} + \Psi u(k-1) \\ Y_{\max} - M_{x_2}x(k) - M_{u_2}u(k-1) \\ -Y_{\min} + M_{x_2}x(k) + M_{u_2}u(k-1) \end{bmatrix}, \tag{41}$$

$$\Lambda = \begin{bmatrix} I & 0 & \cdots & 0 \\ I & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ I & I & \cdots & I \end{bmatrix}_{N_c\times N_c} \quad \Psi = \begin{bmatrix} I \\ I \\ \vdots \\ I \end{bmatrix}_{N_c\times 1}, \tag{42}$$

$$M_{x_2} = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_c} \\ CA^{N_c+1} \\ \vdots \\ CA^{N_p} \end{bmatrix}, M_{u_2} = \begin{bmatrix} CB \\ CAB+CB \\ \vdots \\ \sum_{i=0}^{N_c-1} CA^iB \\ \sum_{i=0}^{N_c} CA^iB \\ \vdots \\ \sum_{i=0}^{N_p-1} CA^iB \end{bmatrix}, \tag{43}$$

$$M_{\Delta u_2} = \begin{bmatrix} CB & \cdots & 0 \\ CAB+CB & \cdots & 0 \\ \vdots & \ddots & \vdots \\ \sum_{i=0}^{N_c-1} CA^iB & \cdots & B \\ \sum_{i=0}^{N_c} CA^iB & \cdots & CAB+CB \\ \vdots & \vdots & \vdots \\ \sum_{i=0}^{N_p-1} CA^iB & \cdots & \sum_{i=0}^{N_p-N_c} CA^iB \end{bmatrix}, \tag{44}$$

where I is the identity matrix of m dimension, and m is the number of control quantities.

According to the aforementioned derivation process, it can be transformed into a quadratic programming problem for a solution. As shown in **formula (45)**, the first item of the solved control sequence is applied to the system, and the control quantity is executed until the next time. At the new time, the system repredicts the output of the next time domain according to the state information. Then, the next new control increment sequence is obtained through the optimization process. This cycle is repeated until the system completes the control process.

$$\begin{cases} \Delta u(k) = \begin{bmatrix} I & 0 & \cdots & 0 \end{bmatrix}\Delta U(k) \\ u(k) = u(k-1) + \Delta u(k) \end{cases}, \tag{45}$$

where k-1 is the last time.

The flexibility margin envelope is drawn according to the calculated control variable sequence, and it is brought into **Eqs 14 – 17** to calculate the indicators of E_{IR}, E_{IO}, and E_{IO}.

The flow chart of the flexibility margin analysis is shown in **Supplementary Figure S4**.

EXAMPLE SIMULATION

Energy Block Parameter Setting

The example system structure is shown in **Supplementary Figure S1**. In the electric- hydrogen coupling energy block constructed in this study, the installed capacity of the wind farm was 60 MW, that of the photovoltaic power generation system was 60 MW, and that of the gas turbine assembly was 30 MW. In terms of the hydrogen energy system, including a 30 MW fuel cell power generation system and 30 MW electrolytic cell system, the initial SOC of hydrogen energy storage was taken as 40%. The energy storage device adopts a battery with a total capacity of 120 mwh, its rated charge discharge power was ±10 MW, and the initial SOC value of the battery was 45%. Refer to the literature (Makarov et al., 2009; Hong, 2013; Kong et al., 2018; Tuinema et al., 2020) for the parameters of matrix *B* in **Eq 25**.

Relevant technical parameters of the electro–hydrogen coupling system are shown in **Supplementary Table S1**.

The data of wind power, photovoltaic, power load, and hydrogen load are shown in **Supplementary Figure S5**.

Flexibility Margin Analysis of the Energy Block

To analyze the differences in flexibility margins in different scenarios, this section designed three calculation scenarios to evaluate the flexibility margins of fast energy.

Scenario 1: In the absence of controllable components, analyze the lack of the flexibility margin in the initial operating state.

Scenario 2: Add hydrogen storage and analyze the flexibility margin of the system.

Scenario 3: Based on scenario 2, battery energy storage and gas generators are added to further increase the adjustment capability of the energy block and analyze the flexibility margin of the system.

The energy block model was established according to each scene, and the system output power at the step size of 5 min was calculated and analyzed. According to the operation of each scene at each time, draw the operation diagram of the energy block and the boundary envelope of the dynamic flexibility margin. The flexibility margin analysis required for scenario 1 is shown in **Supplementary Figure S8**; the simulation analysis of scenario 2 and scenario 3 is shown in **Supplementary Figure S6** and **Supplementary Figure S7** and **Supplementary Figure S8**, and the corresponding flexibility margin boundary envelope analysis is shown in **Supplementary Figure S9** and **Supplementary Figure S10**. The flexibility margin index and flexibility maximum value of each scenario are shown in **Supplementary Table S2** and **Supplementary Table S3**.

In scenario 1, high permeability renewable energy was accessed, and there was no controllable element in the system to adjust. At this time, the air and light rejection can only be adjusted through the overflow energy W, resulting in the mismatch of the flexibility margin of the system and the increase of the flexibility margin index. In scenarios 2 and 3, controllable elements such as hydrogen energy storage and battery energy storage were added. At this time, the flexibility margin of the energy module was effectively increased through the integration of resources. In scenario 2, the flexibility margin requirements of the module in terms of energy storage and output were supplemented through the combination of a fuel cell and electrolytic cell. The operation requirement was to avoid the frequent startup and shutdown of the unit on the basis of full supply of the load and consumption of renewable energy. In scenario 3, the battery energy storage and gas unit further supplement the flexibility margin requirements in the climbing power and unit output required by the module, further improving the flexibility margin level of the system. Scenario two and scenario three supplement the corresponding units based on the flexibility margin index. It can be seen from **Supplementary Table S2** and **Supplementary Table S3** that through the comparison of various scenarios, the integration of controllable resources effectively increases the flexibility margin of the energy module.

As shown in **Supplementary Figure S9, S10**, because of the high proportion of renewable energy connected to the energy module, its strong volatility leads to insufficient upregulation or downregulation capacity at many operation points. For scenario 2, in the 5–33 h interval, there was no wind at night, the fan and photovoltaic output were insufficient, and the climbing power and unit output in the energy module were insufficient, which cannot provide sufficient flexibility resources. During this period, the maximum climbing power shortage was 3.6 MW/min, the maximum output power shortage was 18.5 MW, and the maximum supply power shortage was 4.27 MWh. In the 163–205 h interval, the output of the fan and photovoltaic decreased sharply, the SOC of hydrogen energy storage was maintained at a low level, and the fuel cell cannot provide enough electric energy, so the normal operation of the system can only be maintained through load shedding.

The maximum value of the climbing power shortage during this period was 4.67 MW/min, the maximum value of output power shortage was 20.7 MW, and the maximum value of power supply shortage was 36.27 MWh. In the 42–46, 115, 155–165, 230, 300–310, 325–355 h intervals, energy modules cannot fully absorb renewable energy. These parts of the electricity discarded account for 7% of the total renewable energy power generation. The flexibility margin index of scenario two was E_{IR} = 5.631 MW/min, E_{IO} = 26.173 MW, and E_{IC} = 32.089 MWh. For scenario 3, on the basis of scenario 2, the combination of battery energy storage and gas generator sets makes up for the corresponding flexibility margin deficiency.

It can be seen from **Supplementary Figure S7** that the battery energy storage has the ability to respond quickly. The rapid discharge supplements the system's demand in the climbing power dimension, while the gas-fired unit supplements the lack of output power. Scenario three can basically meet the upward flexibility requirements of the energy modules, but in the 44, 114–115, and 155–160 h intervals, there were still situations where renewable energy power generation could not be fully absorbed. The power discarded in these parts accounts for 1.5% of the total renewable energy power generation. The flexibility margin index of scenario three was E_{IR} = 0 MW/

min, E_{IO} = 1.1MW, and E_{IC} = 3.62 MWh. To avoid the abandonment and load shedding of renewable energy sources, we can invest in flexibility resources with corresponding adjustment capabilities and adjustment directions based on the calculation results.

The Influence of Renewable Energy Penetration Rate on the Flexibility Margin of the Energy Block

Compared renewable energy has the characteristics of intermittency and volatility, and a high proportion of renewable energy access will have a certain impact on the flexibility of the system. According to scenario 3, study the impact of different access ratios of renewable energy on the flexibility margin, gradually increase the ratio of the wind power and photovoltaic access from 0 to 50%, and calculate the abandonment rate of renewable energy by **formula (46)**. The flexibility margin of the system under different penetration rates is shown in **Supplementary Table S4**.

$$E_w = \sum_{t=1}^{N_T} \sum_{i=1}^{2} \frac{P_{gen,i,t}}{P_{gen,i,t} + w_{i,t}}. \quad (46)$$

With the continuous improvement of renewable energy penetration, the flexibility margin of the energy module gradually decreases. As can be seen from **Supplementary Figure S11**, there is a threshold for renewable energy penetration. When the access ratio exceeds 40%, the flexibility margin index of each dimension of the energy module shows a rapid growth trend. The comparison between scenario two and scenario three shows that PV requires a higher flexibility margin than wind power. However, because of the intermittent characteristics of wind power generation, the demand for the flexibility margin in the dimension of climbing power is high. The comparison of different scenarios shows that when the renewable energy penetration rate exceeds 40%, the E_{IC} and E_{IO} indicators increase significantly. When the permeability exceeds 60%, the E_{IC} index increases significantly. It can be seen that the deficiency of the unit output and power supply index has a greater impact on the system flexibility margin.

When analyzing the system flexibility margin, analysis indicators of different dimensions are required. According to the analysis results, the corresponding flexibility margin resources were increased in each dimension to ensure the economy of the system while maintaining the balance of system flexibility margin as far as possible.

CONCLUSION

By analyzing the power exchange characteristics of heterogeneous energy sources, this study established the homogenization model of various flexibility margin resources. On this basis, the energy block model of electro–hydrogen coupling was established. The flexibility margin evaluation index was proposed from the dimension of system operation, and the flexibility margin of the module was analyzed from the three dimensions of climbing power, unit output, and power supply. The model predictive control algorithm was introduced to solve the problem, and then the system flexibility margin was quantitatively analyzed. The conclusions are as follows:

1) By analyzing the power exchange characteristics of heterogeneous energy, a homogenization model was established based on the energy balance relationship of each unit of the energy module. The complex model of multiple physical fields was simplified and equivalent, which lays a model foundation for the online calculation of flexibility margin.
2) In this study, an optimal calculation method of energy block power balance based on MPC was proposed, and the flexibility margin of electro–hydrogen coupling energy block was analyzed. In this study, the energy block balance criterion and flexibility margin index of electro–hydrogen coupling are proposed from the three dimensions of climbing, power, and energy. Through the analysis of the flexibility margin of the operation point, the deficiency of the flexibility margin of the system was judged, the flexibility margin analysis of the energy module was better realized, and suggestions were provided for the system scheduling.
3) The simulation results show that the flexibility index of each operation point is different because of the different intermittent and fluctuation distribution of the energy module at each time. At the same time, nodes and moments with an insufficient flexibility margin can be found according to the drawing of the flexibility margin envelope of operating points. The indicators proposed in this study can help the system coordinate the configuration and operation of flexibility resources.
4) Through the analysis of permeability, it can be seen that there is a threshold of renewable energy permeability. When the threshold is exceeded, the flexibility margin index of each dimension of the energy module shows an increasing trend. Compared with wind power, PV has higher requirements on the flexibility margin.

This study only models from the steady-state dimension and does not involve the transient model of the system and the capacity matching of the wind solar hydrogen system. In the follow-up research, many technical and economic factors such as hydrogen storage and hydrogen sales will be mainly considered. In addition, it is also interesting to investigate the planning and energy management of microgrids and integrated energy systems incorporating the presented electric–hydrogen coupling energy block (Li et al., 2019; Li et al., 2022c).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZH is mainly responsible for technical aspects, conception, and design of manuscripts. SY investigated the homogenization modeling and calculated the main methods. YD contributed to the flexibility margin analysis. SM provided valuable help for calculation. YB and XM participated in the production of the paper chart and the preparation of some content.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.879244/full#supplementary-material

Supplementary Figure S1 | Electro–hydrogen coupling energy module.

Supplementary Figure S2 | Heterogeneous energy homogenization model.

Supplementary Figure S3 | Flexibility margin analysis.

Supplementary Figure S4 | Flowchart of the flexibility margin calculation method.

Supplementary Figure S5 | Value of load, photovoltaic plant output, and wind farms output.

Supplementary Figure S6 | Simulation analysis of scenario 2.

Supplementary Figure S7 | Simulation analysis of scenario 3.

Supplementary Figure S8 | Flexibility margin analysis of scenario 1.

Supplementary Figure S9 | Flexibility margin analysis of scenario 2.

Supplementary Figure S10 | Flexibility margin analysis of scenario 3.

Supplementary Figure S11 | Renewable energy abandonment rate.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

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