

Voltage control method for multi-energy system based on the coupling of renewable energy hydrogen production and storage

Hao Zuo¹ , Yun Teng^{1,*}, and Zhe Chen²

¹ School of Electrical Engineering, Shenyang University of Technology, Shenhao West Road No. 111, Shenyang 110870, Liaoning, PR China

² Energy Technology Center, Aalborg University, Fredrik Bajers vej 5, Aalborg, DK-9220, Denmark

Received: 10 April 2024 / Accepted: 2 July 2024

Abstract. Renewable energy power generation combined with hydrogen storage, is an important way to realize the deep integration of hydrogen energy and renewable energy in multi-energy systems. In the multi-energy system of renewable energy power generation and hydrogen production in AC/DC hybrid. Due to the fluctuation of heat load and electric hydrogen production load in the system and the multi-time scale characteristics of energy flow transmission of heat storage and hydrogen storage. It will lead to the difficulty of power coordination in the whole Multi Energy System (MES). In order to solve the problem of power imbalance in MES, this paper first establishes the hybrid power flow equation of MES cluster composed of AC/DC and hydrogen energy transmission channels. The reactive voltage fluctuation characteristics of the AC/DC system under the fluctuation of energy exchange, system energy conversion, and renewable energy output of the MES cluster interconnection channel are analyzed. Secondly, a multi-energy flow model of the multi-energy system is established. The main factors affecting the voltage-reactive power of the AC system are analyzed. A reactive power model based on electro-thermal conversion, hydrogen storage, and multi-energy transmission channels is established. Then, a generation algorithm of the safe and stable boundary of pipeline pressure is proposed to maintain the pressure of hydrogen production and storage system within a safe range. The robust optimization control method is used to control the coupling of multi-energy sources. Finally, based on the actual operation data of the multi-energy power system. The simulation model of reactive power dynamic optimization control for multi-energy interconnected systems is established. The simulation results show that the control method proposed in this paper is adopted. Through the coordinated distribution of energy among multi-energy systems, the voltage stability level of the system can be effectively improved.

Keywords: Multi-energy system, AC and DC interconnection, Multi-energy trend, Dynamic reactive power control.

1 Introduction

With the continuous advancement and implementation of the energy Internet strategy and the green transformation of energy. Many power grids have gradually developed into Multi Energy System (MES) compatible with various energy sources such as heat and hydrogen. The energy storage capacity of electricity storage, heat storage, and hydrogen storage in these MES is expanding. While effectively improving the operational flexibility of the system, the complexity of the power flow control is also increasing.

In the development of MES. The research on multi-energy coordinated optimization theory and technology such as electrothermal hydrogen is mostly focused on how

to solve the new problems of active power and energy balance in the system. However, the power grid as the core energy network in the MES pays less attention to the problem of reactive power regulation during the multi-energy coordinated operation.

Due to the intermittent fluctuation of wind power and photovoltaic on the time scale. When renewable energy power generation is applied to hydrogen production and storage on a large scale, it is necessary to coordinate with the fluctuation of hydrogen demand in different application scenarios. In order to achieve the synergistic stability of the hydrogen energy system. There have been many studies on large-scale hydrogen production and hydrogen storage system models of renewable energy at home and abroad.

Reference [1] takes the voltage stability of the power system as the control target and establishes the coordinated

* Corresponding author: tengyun@sut.edu.cn

control model of unit layer and upper layer power management. A better system control strategy is obtained. In [2], the MILP model is established by using the branch and bound method. The battery and hydrogen storage tank are used to stabilize the short-term and long-term fluctuations between the power generation side and the load side. Taking the total cost of the electric-hydrogen energy storage system as the optimization objective, the optimal hydrogen production and hydrogen storage capacity configuration is solved. Reference [3] established a multi-objective optimization model with the optimization objectives of wind curtailment, load power shortage rate, and fluctuation. The fast non-dominated sorting genetic algorithm is used to solve the optimal hydrogen production and storage capacity configuration, and better optimization results are obtained.

Reference [4] modeled the power system, hydrogen system, and coupling link separately and verified the applicability of the model. Reference [5] established an integrated framework for power, hydrogen, and methane systems to verify the improvement of the flexibility of the integrated energy system by the coupling of the three.

In the current MES, the problem of voltage coordination control between AC/DC multi-energy grids is less involved. The formation of a large-scale AC/DC multi-energy interconnect system will be more complicated. The problem of active and reactive power balance will also become more prominent. Whether the traditional reactive power control strategy/tgcqais applicable to the new multi-energy interconnected system is one of the key issues related to the operational stability of large-scale multi-energy interconnected systems.

Reference [6] addresses the problem of voltage instability caused by centralized access to large-scale renewable energy sources. A regional voltage-coordinated control strategy for renewable energy generation is proposed. Literature [7] proposes a complementary structure for the operation of a multi-type electrolyzer system. Improving the configuration ratio of different types of electrolysis tanks in the system to realize the improvement of the overall electrolysis system energy characteristics and economy under fluctuating power supply. In terms of hydrogen production efficiency improvement. Literature [8] proposes a hydrogen production efficiency improvement strategy based on segmented fuzzy control. By constructing an optimal scheduling model under hydrogen production efficiency improvement, the artificial bee colony algorithm is used to solve the problem, which ensures that the efficiency of the electrolyzer is improved while guaranteeing the safety of hydrogen production.

Literature [9] Operating characteristics of electric, hydrogen, and thermal microenergy systems. A suitable hierarchical optimization coordination control strategy and its implementation framework are proposed. It includes three parts: a coordinated control layer, an optimized control layer and, an executive control layer. In the design of the control process, the singular perturbation theory is adopted and the time scale and operating characteristics of the electric, hydrogen, and thermal subsystems are fully considered. Time decomposition of different energy system

control measures and optimal scheduling of different energy forms. Thereby achieving effective management of electricity, hydrogen, and heat micro energy systems. Literature [10, 11] proposes to use the hydrogen production system to absorb the fluctuations of wind power to provide stable power for the grid. The entire MES has not been optimized. And the method of EMR modeling is adopted. This method can visually express the energy transfer model. However, the control results for the entire system do not necessarily reach an optimal state. The control system is only controlled by a single multi-energy microgrid.

With the formation of MES clusters formed by the connection of AC and DC lines and hydrogen pipelines, the scale and complexity of the AC/DC system continue to develop. The links between multi-energy networks are getting closer. The interaction between the volatility and uncertainty of renewable energy can not be ignored. The power flow equations in traditional power systems are no longer suitable for MES [12–15]. Therefore, it is necessary to study the power flow equation for establishing a MES. An analysis of reactive coupling characteristics between clusters of MES. Coordinated and optimized control of reactive voltage problems in MES clusters.

At present, there are the following problems in the research of electric hydrogen production: in the case of renewable energy input fluctuation, the overall energy utilization rate of electric hydrogen production power plant, and the efficiency optimization control of electric hydrogen production device. It is difficult to effectively and efficiently consume renewable energy power generation by studying a single hydrogen production device. When the electric hydrogen production and energy storage device work together. It is difficult to reasonably allocate the power of the two and the state of charge (SOC) of the energy storage device. In order to solve the above problems, this paper adopts a multi-source energy storage method based on the combination of power storage, heat storage, and hydrogen storage. The energy storage coordination optimization is carried out for the power fluctuation problem under different conditions, and the coupling relationship between the multi-energy flows of the multi-energy system is systematically modeled. Through the coordination of power storage, heat storage, and gas storage, the consumption level of new energy is further improved. The voltage stability of the system is improved under the premise of maintaining the pressure stability of the pipeline network.

The first point of the article summarizes the research status at home and abroad. The main methods of current research are discussed. The second part of the article establishes the MES cluster hybrid power flow equation. The coupling characteristics of each energy subsystem in the multi-energy system are obtained. In the third part of the article, the electric heating model and the electric gas model are established. The reactive power demand characteristics of the AC/DC system of electric heating devices and electric gas devices are analyzed. In the fourth part of the paper, the energy transmission model of the multi-energy system is established. In the fifth part, an algorithm for generating the safe and stable boundary of pipe network pressure is proposed. Maintain the pressure of hydrogen

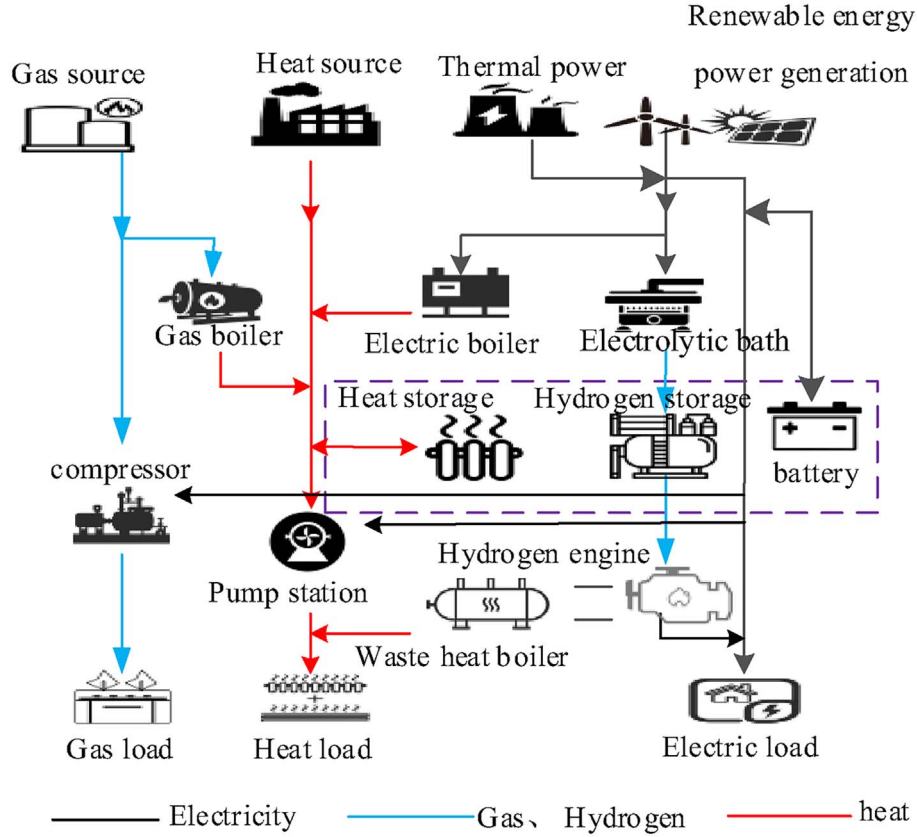


Fig. 1. MES cluster model.

production and hydrogen storage system within a safe range. The reactive power robust optimization flow chart of the AC/DC system is given. The sixth part is simulation verification. The seventh part is the conclusion of the article.

2 MES cluster hybrid power flow model

2.1 Modeling of coupled MES

Assume that the MES cluster is formed by the AC/DC transmission channel. Each multi-energy network has a conversion between electric energy, hydrogen, and multiple energy sources. Each multi-energy network has independent control switches. Control the connection to the AC and DC bus of the cluster system. For MES, power generation, energy storage. The load demand is coordinated to maintain the system's reactive balance.

Larger scale energy conversion capacity exists in MES clusters. Therefore, in an MES, the stable operation level of the system can be improved by coupling control between different energy sources. At the same time, there are different energy forms of energy conversion and coordination balance between multiple energy system clusters. It will affect the reactive dynamic balance of the MES formed by the AC/DC transmission channel.

A MES cluster diagram is shown in Figure 1.

2.2 AC/DC hybrid MES cluster power flow model

Firstly, the power balance model of the AC/DC interconnected system is established. The MES cluster power flow equation is [16]

$$\begin{cases} P_{Ei}^s - \sum_{j \in i} P_{Eij}(U_i, U_j, \theta_i, \theta_j) + \alpha P_{Ei} = 0 \\ Q_{Ei}^s - \sum_{j \in i} Q_{Eij}(U_i, U_j, \theta_i, \theta_j) - Q_{Ei} = 0 \\ P_{Gi}^s - \sum_{j \in i} P_{Gij}(\mu_i, \mu_j, \beta_i, \beta_j) - \lambda P_{Gi} = 0 \\ Q_{Gi}^s - \sum_{j \in i} Q_{Gij}(\mu_i, \mu_j, \beta_i, \beta_j) - Q_{Gi} = 0 \end{cases} \quad (1)$$

where: P_{Ei}^s and Q_{Ei}^s are the active and reactive power of the injected nodes in the MES cluster. P_{Eij} and Q_{Eij} are the active and reactive power of node i to node j in the MES cluster. U_i and θ_i are the voltage amplitude and voltage phase angles of the nodes in the MES cluster. U_j and θ_j are the voltage amplitudes and phase angles of adjacent nodes j in the MES cluster, respectively. P_{Ei} and Q_{Ei} are active power and reactive loss at node i ; α is a signal variable that is connected to the rectifier or inverter. When the node is connected to the rectifier, α takes -1 , and when the node is connected to the inverter, α takes 1 . P_{Gi}^s and Q_{Gi}^s are the power flow active and reactive power

corresponding to the volume flow of the hydrogen pipeline injected into node i . μ_i is the compression ratio of hydrogen at node i . β_i is the temperature of the hydrogen at node i . μ_j is the compression ratio of hydrogen at node j . β_j is the temperature of the hydrogen at node j . λ is the compressor loss factor.

The constraint equation for the energy transport channel of an MES cluster is

$$P_G = g_{as}S \quad (2)$$

where g_{as} is the low calorific value of hydrogen. S is the hydrogen flow volume. P_G is the power flow corresponding to the volume flow of the hydrogen pipeline.

The mixed flow correction equations of the MES from equations (1) and (2) is:

See the Equation (3) bottom of the page

where Q_d is the reactive power column vector in the DC transmission unit. P and Q are node active power and reactive power column vectors. ΔP and ΔQ are node active power and reactive power unbalanced column vectors. ΔP_G and ΔQ_G are the active power and reactive power imbalance column vectors of the equivalent power flow at the hydrogen network node. I_d and ΔI_d are direct current column vector and DC current correction column vector of DC transmission unit. ΔU and $\Delta \theta$ are the corrected magnitude column vector of the node voltage amplitude and phase angle, respectively. U is the node voltage amplitude column vector. P_d and ΔP_d are the DC active power column vector and the DC active power unbalanced column vector in the DC power transmission unit.

3 Reactive characteristics of electric heat transfer in MES

3.1 Reactive power voltage model of electric heating device in MES

Simplify the MES topology with large-scale electric boilers and other forms of electric heating. The electric boiler in the system, as well as the electric heating and electric heat storage devices, can be equivalent to the resistance element. Therefore, the schematic diagram of the system active and

reactive power sinking into the grid in a MES is shown in Figure 2.

In the topology diagram, $P + jQ$ represents the active power and reactive power of the renewable energy grid connected to the MES. $R_1 + jX_1$ represents the equivalent line impedance of the grid transmission line in clean energy power station 1. $R_n + jX_n$ represents the equivalent line impedance of the transmission line of the clean energy power station n .

By analyzing the influence of the active demand change of the electrothermal conversion device on the grid voltage. This process provides an ideal voltage source for the low side of the substation. The u_1 phasor is used as a reference for the grid voltage. According to Kirchhoff's voltage law, the grid point voltage u_{pcc} can be expressed by the following formula [17]

$$u_{pcc} = R_n \dot{I}_n + jX_n \dot{I}_n + u_1 \quad (4)$$

where $R_n + jX_n$ represents the equivalent line impedance, $\dot{I}_n$ represents the grid-connected current. n represents the number of branches.

The equivalent impedance of the line increases due to the access of the resistive element. This causes a certain voltage deviation. When the active power increases. In an inductive power network, the grid-connected voltage u_{pcc} phase leads the grid voltage u_1 to some extent. Continuous investment in electrothermal conversion devices. The phase difference between the voltage phase of the grid point and the grid voltage is gradually reduced. Therefore, when the electric boiler is continuously put into operation. The active power consumed by the resistive element R in the line increases. The power input of the grid connection is reduced. The reduction in active power output leads to a certain increase in the voltage at the grid point. Therefore, during the switching process of the electric heating device. When ensuring the active demand of the system, it is necessary to deliver a certain reactive power to ensure the suppression of active fluctuations and voltage fluctuations.

Through the above analysis of the influence of the electrothermal conversion device on the reactive power of the grid, the reference voltage of the grid connection point is set to

$$U_{pcc} = U + \frac{PR_n + QX_n}{U}. \quad (5)$$

$$\begin{bmatrix} \Delta P_d \\ \Delta P \\ \Delta Q \\ \Delta P_G \\ \Delta Q_G \end{bmatrix} = \begin{bmatrix} \frac{\partial P_d}{\partial I_d} & \frac{\partial P_d}{\partial U} U & 0 & 0 & 0 \\ \frac{\partial P_d}{\partial I_d} & \frac{\partial P}{\partial U} U + \frac{\partial P_d}{\partial U} U & \frac{\partial P}{\partial \theta} & 0 & 0 \\ \frac{\partial P_d}{\partial I_d} & \frac{\partial Q}{\partial U} U + \frac{\partial Q_d}{\partial U} U & \frac{\partial P}{\partial \theta} & 0 & 0 \\ \frac{\partial P_d}{\partial I_d} & \frac{\partial Q}{\partial U} U + \frac{\partial Q_d}{\partial U} U & \frac{\partial P}{\partial \theta} \frac{\partial P}{\partial \mu} \mu + \frac{\partial P_G}{\partial \mu} \mu \frac{\partial P_G}{\partial \beta} & \frac{\partial P}{\partial \theta} \frac{\partial Q}{\partial \mu} \mu + \frac{\partial Q_G}{\partial \mu} \mu \frac{\partial P_G}{\partial \beta} & \frac{\partial P_G}{\partial \theta} \frac{\partial Q}{\partial \mu} \mu + \frac{\partial Q_G}{\partial \mu} \mu \frac{\partial P_G}{\partial \beta} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta U \\ \Delta \theta \\ \Delta \mu \\ \Delta \beta \end{bmatrix} \quad (3)$$

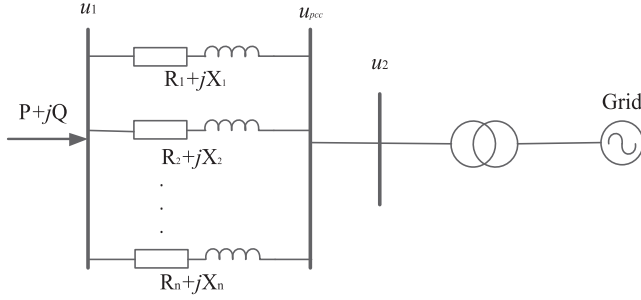


Fig. 2. Electric heating device connected to the grid model.

As the number of electric boilers in the system increases, the active power of the grid is reduced. The QX_n in the above equation increases when the magnitude of the PR_n reduction is greater than the magnitude of the QX_n increase. The voltage at the system's grid point drops. As the thermal load increases in the system, the voltage at the grid point decreases. When the output of renewable energy is constant and the input capacity of the electric boiler is constant, the system voltage is constant, and the reactive power required by the system is

$$Q_{\text{iref}} = \frac{U_{\text{pcc}} U - U^2 - PR_n}{X_n} \quad (6)$$

3.2 Reactive voltage model of MES hydrogen storage system

When the AC line is running stably, the line voltage remains basically the same. The analysis of Figure 3 shows that the equivalent reactive energy consumption model with multiple hydrogen storage systems is [18]

$$Q_c = (P_h^2 + Q_h^2)X/U^2 - U^2\omega \sum_{i=1}^n C_z l_i \quad (7)$$

$(P_h^2 + Q_h^2)X/U^2$ is the reactive power that the AC system needs to consume. P_h , Q_h is the active power and reactive power flowing into the system; X is the line reactance, U is the AC line voltage, C_z is the equivalent capacitance of the hydrogen storage device in the AC line, ω is the system frequency, and l_i is the i th line length. Through the above analysis, the active and reactive expressions of the hydrogen storage system in the MES are obtained.

After accessing the hydrogen storage device, the active and reactive power of an MES in the grid point is expressed as [19]:

$$P_{\text{ib}} = \frac{U_{\text{pcc}} U_i}{X_i + X_{Li}} \delta_i \quad (8)$$

$$Q_{\text{ib}} = \frac{U_{\text{pcc}}(U_i - U_{\text{pcc}})}{X_i + X_{Li}} \quad (9)$$

where: U_i represents the output voltage amplitude of the i th line in the line. δ_i is the phase angle difference between the output voltage of the hydrogen storage device i and

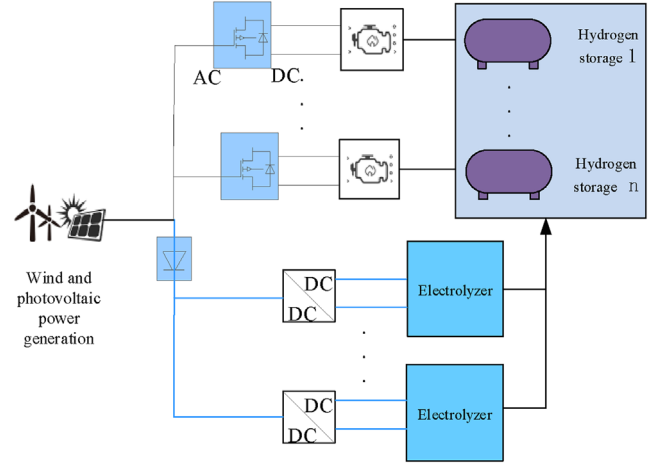


Fig. 3. Reactive voltage model of hydrogen storage device in MES.

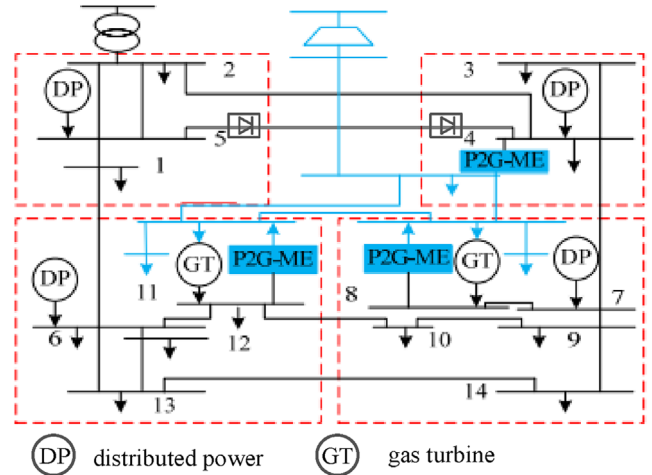


Fig. 4. Energy transfer and conversion system diagram between multiple energy systems.

the grid-connected point voltage. $X_i = Z_i \sin \theta_i$ Z_i is the output impedance of the i th line. θ_i is the output impedance angle. $X_{Li} = Z_{Li} \sin \theta_{Li}$ Z_{Li} is the line impedance. θ_{Li} is the line impedance angle.

4 Multi-energy flow model

Figure 4 shows a schematic diagram of the energy transfer and conversion system between MES.

Set in unit time, for the cogeneration unit, the conversion efficiency during the conversion of electric energy is

$$\eta_{\text{el}} = \frac{E_{\text{el}}}{E_{\text{oth}}} \quad (10)$$

E_{el} is the generated electrical energy. E_{oth} is the other form of energy consumed.

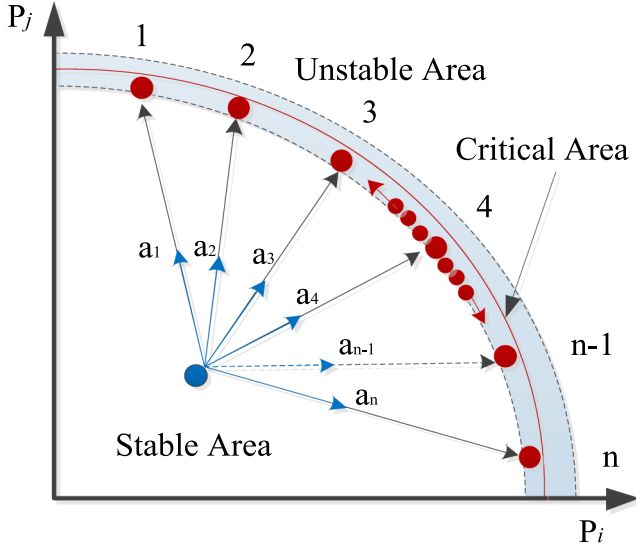


Fig. 5. Schematic diagram of search security boundary.

In the process of converting electric energy, the utilization efficiency of heat is η_{ho}

$$\eta_{ho} = \frac{E_{hou}}{E_{oth}} \quad (11)$$

E_{hou} is the output of thermal energy. In the electrothermal conversion process, the conversion efficiency for the electrothermal conversion device is

$$\eta_{ho} = \frac{E_{h,HP}}{E_{el,HP}} \quad (12)$$

$E_{h,HP}$ is the thermal energy output. $E_{el,HP}$ is the power consumed.

For the primary energy consumption is

$$E_{fu,G} = \frac{E_{el,G}}{\eta_G} \quad (13)$$

$E_{el,G}$ is the total output power of the grid. η_G is the conversion efficiency of electric energy.

Through the above calculations, the energy consumption of the entire energy network can be obtained as

$$E_{el,G} + E_{el} + E_{el,RES} - E_{el,HP} = E_{el,A} \quad (14)$$

$E_{el,G}$ is the amount of electricity generated by the hydrogen turbine. E_{el} is the electricity generated by the cogeneration unit. $E_{el,RES}$ is the electrical energy emitted by renewable energy sources. $E_{el,HP}$ is the electrical energy consumed by the electrical heating process. $E_{el,A}$ is the power demand of the power system.

Analysis by the above model. It can be concluded that the energy flow of the MES has a reactive effect on the system expressed as

$$E_{el,A} = \frac{Q_{el}}{U_{el}} dU_{el} \quad (15)$$

Q_{el} is the reactive power injected into the system. U_{el} is the injection point voltage.

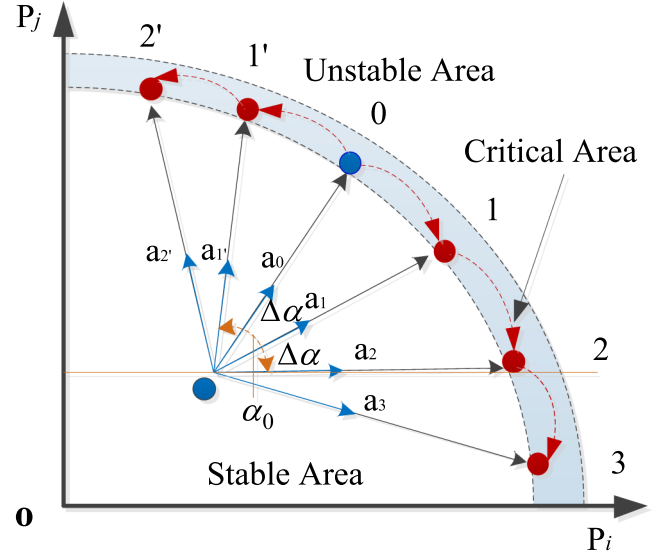


Fig. 6. Improved search security boundary diagram.

4.1 Reactive demand model for multi-energy energy transport

Thermal energy, hydrogen, etc. need to be transported through pipelines. The reactive power compensation capacity of the asynchronous motor in the transmission pipeline pumping station fluctuates with the flow fluctuation in the transmission pipeline. The following is an analysis of the reactive power requirements of the transmission line.

In the process of long-distance energy transmission. Because the hydrogen such as hydrogen is transmitted in the pipe network, there is friction. Therefore, it is necessary to pressurize during the transmission process to overcome the energy loss during transmission and the work done to overcome potential energy.

The equilibrium relationship that the liquids in the pipeline meet is [20]

$$\frac{1}{\rho} \frac{\partial Y_{pre}}{\partial l} + v_l \frac{\partial v_l}{\partial l} + \frac{\partial v_l}{\partial t} + g \sin \psi + \frac{f v_l |v_l|}{2Dg} = 0. \quad (16)$$

In the above formula, ρ is the density of the liquid. Y_{pre} is the pressure per unit of liquid in the cross-section of the pipe. l is the length of the pipe. v_l is the flow rate of the liquid and g is the acceleration of gravity. ψ is the angle of inclination of the pipe. D is the diameter of the transmission pipe. f is the coefficient of friction damping.

The reactive power of the energy flows to the pumping station. This can be expressed by the following formula

$$\begin{aligned} Q_{bc} &= P_y (\tan \varphi_1 - \tan \varphi_2) \\ &= P_y \left(\sqrt{\frac{1}{\cos^2 \varphi_1} - 1} - \sqrt{\frac{1}{\cos^2 \varphi_2} - 1} \right) \end{aligned} \quad (17)$$

Q_{bc} is the reactive power demand of the grid in an MES. $\tan \varphi_1$ is the tangent of the power factor angle of the current system. $\tan \varphi_2$ is the tangent of the power factor angle when the system is balanced. $\cos \varphi_1$ is the power factor of

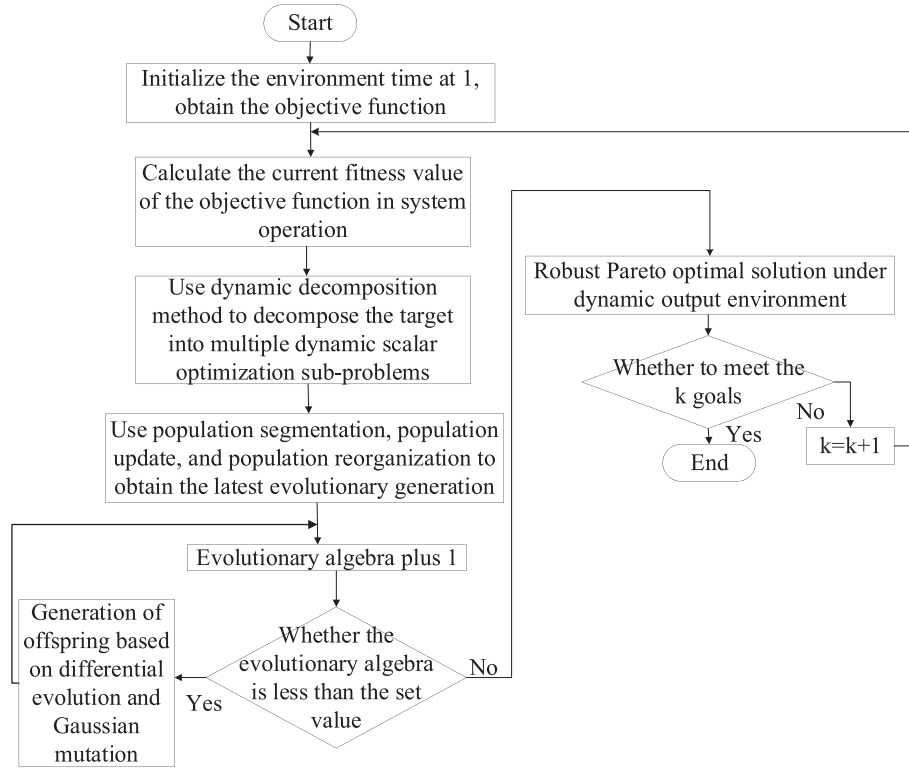


Fig. 7. Robust control optimization process.

the current system. $\cos\varphi_2$ is the power factor that maintains the system's reactive power balance. P_y is the active power delivered by the pump station.

$$P_y = gZ + \frac{\pi\left(\frac{D}{2}\right)^2 Y_{\text{pre}}}{\rho} + \frac{v_l^2}{2} \sum h_f \quad (18)$$

In the above formula, ρ is the density of the liquid.

Y_{pre} is the pressure per unit of liquid in the cross-section of the pipe. v_l is the flow rate of the liquid. g is the acceleration of gravity. Z is the vertical height of liquid transport during transport. $\sum h_f$ is the work done by the liquid to overcome the friction of the pipe during transmission.

4.2 Reactive power demand model in MES

In MES, energy storage units and clean energy power plants provide active and reactive power. Energy storage systems and clean energy power plants are usually connected to the grid through inverters.

Adjusting the inverter allows the energy storage to have a certain reactive power adjustable capacity while emitting/absorbing active power. Clean energy power generation reactive power output constraint can be expressed as [21]

$$(P_{\text{FB},i})^2 + (Q_{\text{FB},i})^2 \leq (S_{\text{FB},i}^{\text{max}})^2 \quad (19)$$

$P_{\text{FB},i}$ contributes to clean energy generation. $Q_{\text{FB},i}$ contributes to clean energy generation. $S_{\text{FB},i}^{\text{max}}$ is the maximum apparent power for the grid connection of clean energy generation systems.

Based on power factor constraints at the grid point of clean energy generation. The constraint expression is:

$$0.95 \leq \frac{|P_{\text{F},i} - P_{\text{FB},i}|}{\sqrt{(P_{\text{F},i} - P_{\text{FB},i})^2 + (Q_{\text{F},i} - Q_{\text{FB},i})^2}} \leq 1 \quad (20)$$

4.3 Reactive power equivalent model MES cluster

In a MES cluster. The reactive power loss of the AC-DC grid is mainly the loss of the energy transmission and transformation process of the MES cluster. The reactive power loss of the pipe network transmission in the MES. Therefore, the reactive power injected into the grid by the MES cluster can be expressed by the following formula

$$Q = \sum_{n=1}^N Q_{\text{dn}} + \sum Q_{\text{bc}} - \sum Q_{\text{lin}} - \sum_{j=1}^N Q_{\text{tn}} - \sum Q_{\text{T}} \quad (21)$$

$\sum_{n=1}^N Q_{\text{dn}}$ is the sum of the reactive powers of all power supplies in a MES with n clusters. $\sum Q_{\text{bc}}$ is the sum of the output of the reactive power compensation device in the system. $\sum Q_{\text{lin}}$ is the reactive power loss of the entire cluster system. $\sum_{j=1}^N Q_{\text{tn}}$ is the reactive loss of the switching device in the N renewable energy generating units. $\sum Q_{\text{T}}$ is the sum of reactive power consumed by the pipe network system.

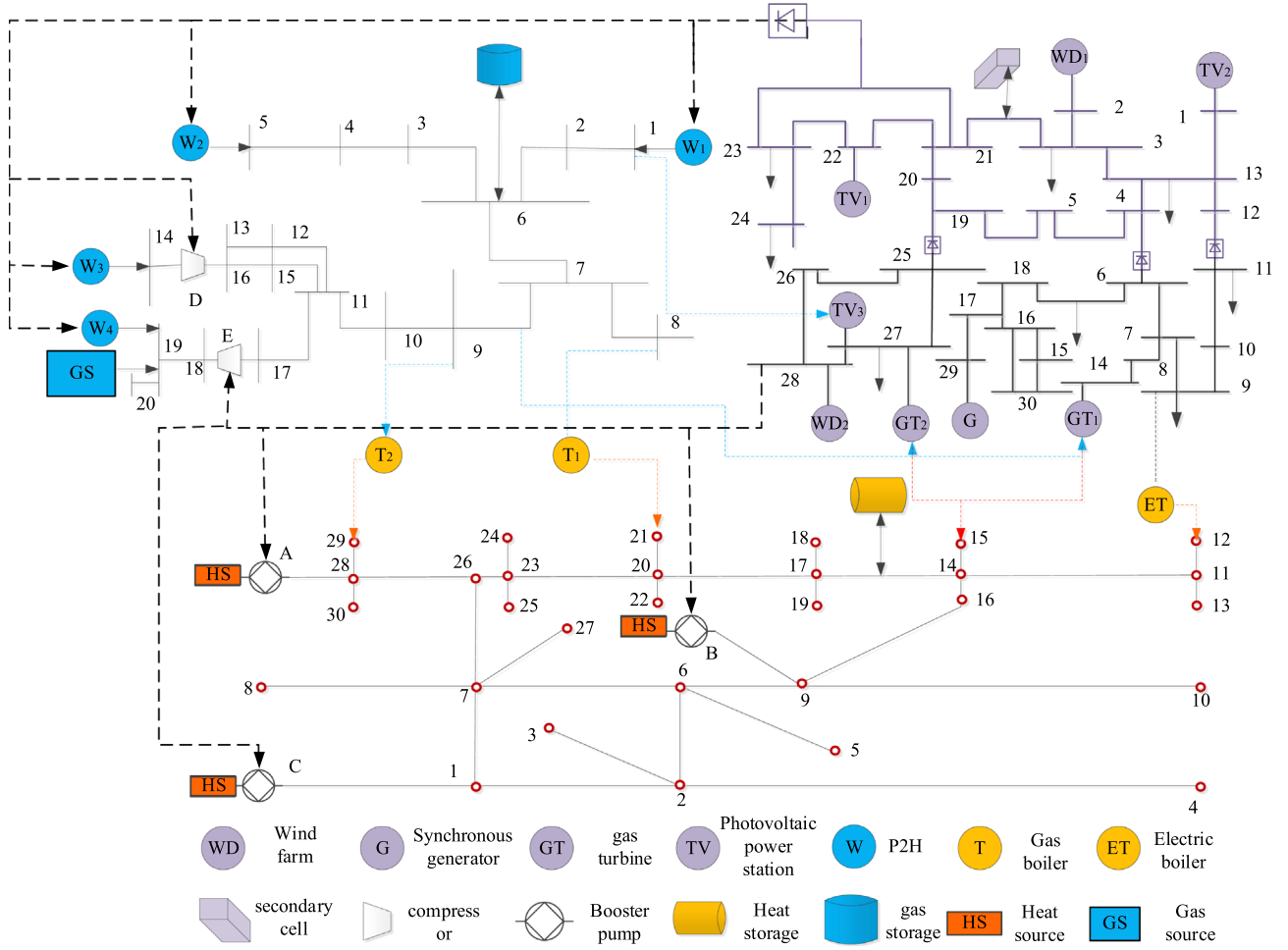


Fig. 8. MES with AC/DC hybrid cluster network.

5 Generation of pipeline pressure stability boundary of hydrogen storage system

In a MES, the safety and stability limit of pipeline network pressure is restricted by multiple factors. In order to ensure the safe and stable operation of the MES, a proposed algorithm for generating the safety and stability boundary of pipeline network pressure is presented. By generating safe and stable boundary sample data, it is used to construct the safe and stable boundary of the system pipe network. This method reduces part of the data samples far away from the boundary to a certain extent, ensuring the reliability of the safety and stability boundary data of the pipeline network pressure.

The pipe network system pressure safety and stability boundary is the collection of all critical operating points when transmission power reaches its limit. The search for the pressure safety and stability boundary of the pipe network is conducted by searching for the critical point of pressure stability. The search for the critical point of pressure stability can be described as: Under a given power growth direction, calculate the process from the current operating point to the limit point of pipeline pressure transmission. When

satisfying various security constraints, take the pipe network a-b as an example. Construct the corresponding pipeline pressure safety and stability boundary in the pipe network system. According to the above characteristics, when the power injected by the pumping station increases. Within the safe range of pipe network pressure, the search model for the critical point of pressure stability corresponding to branch a-b is

From Figure 5, we can see that with the increase of the transmission capacity of the pipe network system. When the pipeline transmission pressure increases. The pressure stability critical point on the safety and stability boundary is located in the finite neighborhood of the stable point to be searched. Take advantage of this feature further. Improved the search efficiency of pipeline pressure critical safety points in the pipeline network system effectively. Therefore, proposed a new fast search model for safety critical-points.

$$\begin{cases} \max \Delta \Gamma_{\text{Pai}} \\ \text{s.t.} \begin{cases} f(\mathbf{x}_{i-1}, \mathbf{y}_{i-1}) - (\Gamma_{\text{Pa}(i-1)} + \Delta \Gamma_{\text{Pai}}) \mathbf{b}_i = 0 \\ P_{a-b} \leq P_{a-b}^{\max} \end{cases} \end{cases} \quad (22)$$

Table 1. Parameters of new energy AC/DC hybrid grid.

DC transmission/MW	Fire power installed/MW	Wind power installed/MW	Photovoltaic installation machine/MW	Power storage capacity/MW · h	Heat storage capacity/MW · h	Hydrogen gas storage capacity/MW · h
20	30	26	21	10	5	10

Table 2. Pump station parameters.

Parameter	Coupling nodes A	Coupling nodes B	Coupling nodes C	Coupling nodes D	Coupling nodes E
Flow/(m ³ · h ⁻¹)	989.5	725.1	752	656	619
Power factor	0.92	0.93	0.93	0.92	0.92
Input active power/MW	2.47	2.38	2.27	2.51	2.29
Input reactive power/MVar	1.69	1.11	1.18	1.39	1.61
Unit efficiency %	88.4	89.1	87.6	84.1	87.1
Pipe diameter/mm	530	273	530	890	890

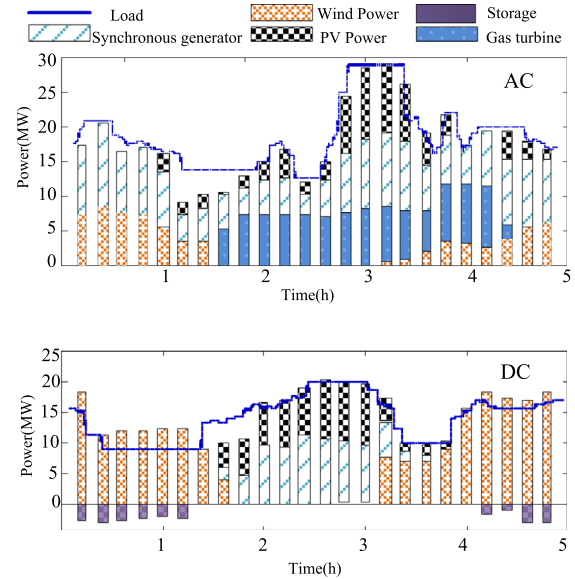
where Γ_{Pai} is the pressure safety and stability margin of the system in the direction of transmission power increase $\mathbf{b}_i$. $\Delta\Gamma_{\text{Pai}}$ is the difference between the system stability margin Γ_{Pa} in the power increase direction $\mathbf{b}_i$ and the system stability margin $\Delta\Gamma_{\text{Pa}(i-1)}$ in the power increase direction $\mathbf{b}_{i-1}$. $f(x)$ is the medium flow transmission equation of the pipe network. $P_{a-b}^{\max}$ is the maximum pressure that branch $a-b$ can withstand.

The optimization model established by formula (22) is used to quickly search the security boundary, and the schematic diagram is shown in Figure 3. Take $\mathbf{o}$ as the starting point, search along the initial power growth direction $\mathbf{b}_0 = [\dots, \Delta P_{i,0}, \dots, \Delta P_{j,0}, \dots]^T$ to obtain the pressure stability limit point 0 when the branch $e-f$ energy transmission reaches its limit. At the two-dimensional injection space shown in Figure 6. The direction angle of power increase corresponding to the pipe network pressure stabilization point 0 is α_0 . The safety and stability margin is $\Gamma_{\text{Pa}0}$. The coordinates are $(\Gamma_{\text{Pa}0}\Delta P_{i0}, \Gamma_{\text{Pa}0}\Delta P_{j0})$.

Set the direction angle of pipeline pressure to increase step size is $\Delta\alpha$. Searched the system's pressure stability critical point along the direction of pressure direction angle decrease. Searched for the critical point of system pressure stability. Searched for the critical point of system stability. Let $\alpha_1 = \alpha_0 - \Delta\alpha$. Change the pressure growth direction of the pipe network system to $\mathbf{b}_1 = [\dots, \Delta P_{i,1}, \dots, \Delta P_{j,1}, \dots]^T$

$$\begin{cases} \Delta P_{i1} = |\mathbf{b}_0| \cos \alpha_1 \\ \Delta P_{j1} = |\mathbf{b}_0| \sin \alpha_1 \\ |\mathbf{b}_0| = \sqrt{(\Delta P_{i0})^2 + (\Delta P_{j0})^2} \end{cases} \quad (23)$$

Let $\Gamma_{\text{Pa}1} = 0$, and take the thermal stability critical point 0 as the initial point of equation (22). The parameter values x_0 , y_0 and $\Gamma_{\text{Pa}0}$, as the initial value of the optimization model proposed in equation (22). Search for the difference $\Gamma_{\text{Pa}1}$ between the relative pressure of the system in the pressure increase direction $\mathbf{b}_1$ and the system pressure safety

**Fig. 9.** Coordination between power and energy storage.

margin in the increase direction $\mathbf{b}_0$. Then obtain the critical point of system pressure stability 1. Similarly, the critical points 1', 2', 3' of the system pressure stability in the increasing direction of α can be searched. Then the stability boundary of the branch $a-b$ in the two-dimensional space of the pressure increases at nodes i and j .

In this paper, the robust optimization control method of a multi-energy system based on an improved genetic algorithm is adopted, and the specific process is shown in Figure 7 [22].

6 Simulation

The multi-source energy storage simulation experimental platform shown in Figure 8 is built in MATLAB/Simulink.

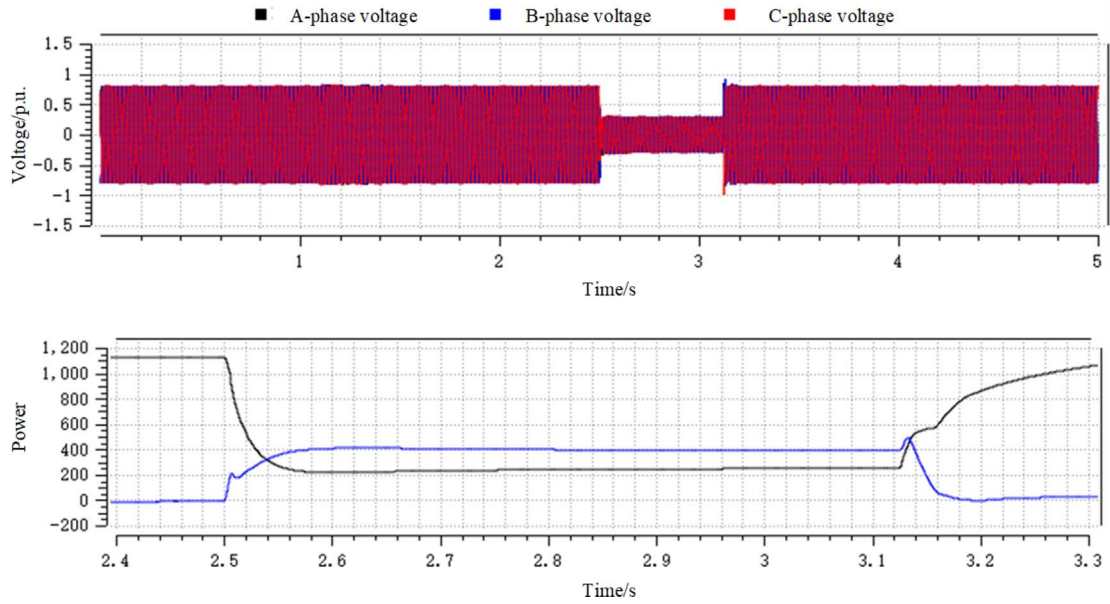


Fig. 10. Simulation results of system voltage fluctuation.

The parameter table in the system is shown in Tables 1 and 2. Applied the multi-energy storage collaborative configuration method to the AC/DC power grid, heating network, and Hydrogen gas network coupling system.

The MES composed of a power system, thermal system, and gas hydrogen hybrid system. AC/DC power grid load, power supply, energy storage and DC transmission capacity parameters are shown in Table 1. The pipeline transmission flow rate and the relevant parameters of the pumping station are shown in Table 2.

When the demand for hydrogen and thermal energy increases, it is necessary to start the pressure of station to increase the thermal network or hydrogen network. At this time, the reactive power required in the pumping power grid increases, and the reactive power demand at different nodes of the AC/DC system also changes accordingly. When the unreasonable demand in the multi-energy AC/DC system suddenly increases, the node voltage decreases due to insufficient reactive power in the system. After optimizing of multi-energy AC/DC system with robust control, it can be realized energy conversion between multi-energy systems. By coordinating and optimizing the voltage stability of the system, the coordination relationship between the power supply, thermal source, and the hydrogen source in the system is showed in Figure 9.

The voltage fluctuation caused by the change of renewable energy output in the system is simulated respectively, as shown in Figure 10, under the case of large renewable energy output, the model completes the start-up before 1 s; the power increases in 1.1 s, and the power reaches 0.9 times of the rated capacity in 2.4 s; the three-phase voltage of the grid falls to 20% in 2.5 s~3.12 s, enters the low-voltage penetration state in 2.5 s, and does not go off the grid in 625 ms after entering the low-voltage penetration state in 3.15 s. At 2.5 s~3.12 s, the three-phase voltage drops to 20% of the rated capacity; at 2.5 s, it enters the low-voltage penetration state; at 3.15 s, it leaves the

low-voltage penetration state, and it is not disconnected from the grid within 625 ms after entering the low-voltage penetration state, which indicates that the coordinated control among individual energy sources in the MES can maintain voltage stability.

As shown in Figure 11, in the case of large renewable energy output. Start-up is completed before 1 s, power is added at 1.1 s, and power reaches 0.9 times the rated capacity at 2.4 s. The three-phase voltage of the grid rises to 130% at 2.5 s~3 s, enters into the high-voltage penetration state at 2.5 s, and comes out of the high voltage penetration state at 3 s, and does not come off the grid within 500 ms after entering into the high penetration state, and the individual energy sources of a MES are able to maintain voltage stability by coordinated control. The coordinated control between the energy sources in the MES can maintain voltage stability.

Figures 12 and 13 are the change waveform diagram of the DC voltage when the renewable energy power of the renewable energy in the AC grid fluctuates and the DC load increases at the same time. It can be seen by comparison that without the control of robust control, the disturbance can cause the DC voltage to appear peaks and fluctuations during the adjustment process. In the case of the control of voltage robust control, the DC voltage transitions slowly and smoothly to the stable state value. Therefore, the robust control method can effectively suppress the effects of AC voltage disturbance on the dynamic response of DC voltage.

It can be seen from Figure 14 that in the multi-energy system of AC/DC mixed connection, when the control method is not used robust optimization, the node 12 and 25 voltage appears higher than 1.05 p.u. from 6:30 h to 7 h. From 7:30 to 9:30, the node voltage in the grid is lower than 0.95 p.u. This is due to the less load in the early morning. When of the wind power suddenly increases, the voltage will increase in short term. When the load increased

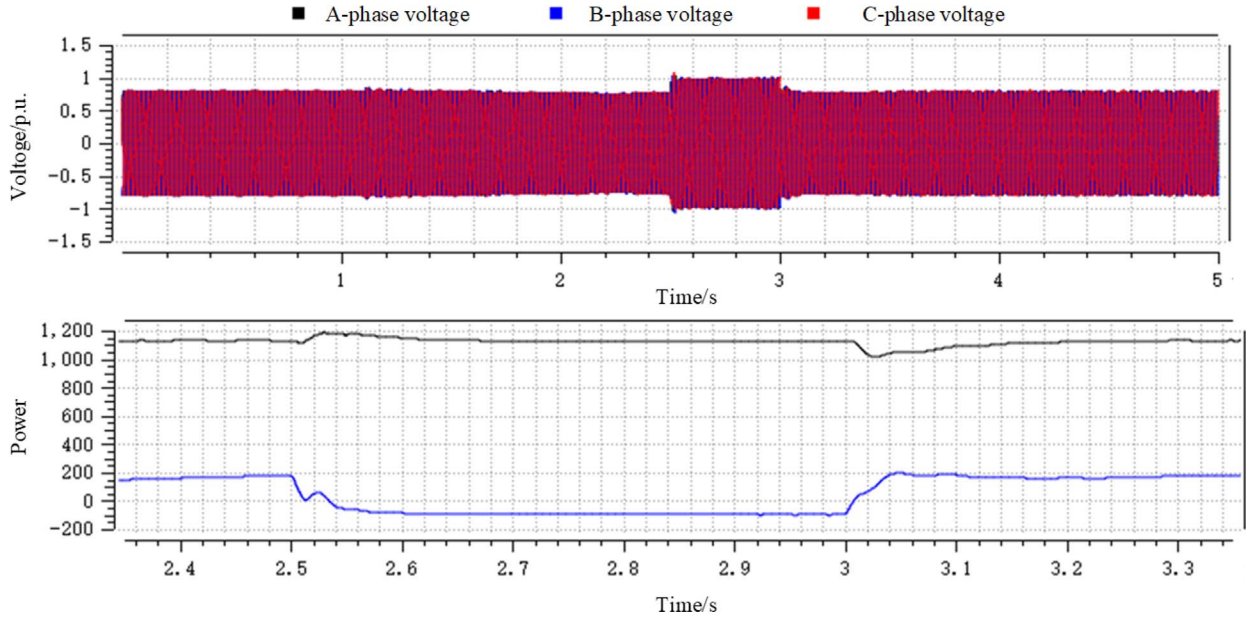


Fig. 11. Simulation results of system voltage fluctuation.

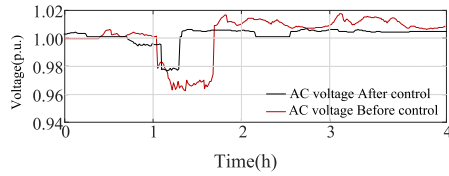


Fig. 12. AC voltage waveform.

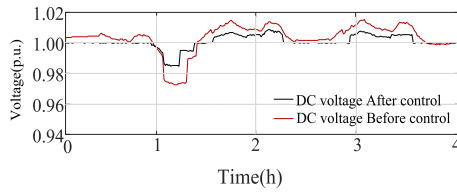


Fig. 13. DC voltage waveform.

suddenly in the morning and afternoon, the voltage decreased when the distributed power supply was small. After using the robust control method, the storage device is charged at night, and released during the peak of the load. Coordinate the energy to improve the voltage of grid nodes.

Figure 15 shows that the DC voltage changes waveforms under different control effects when different degrees of load fluctuations occur in DC power grids. It can be seen from Figure 11 that when the DC load increases by 0.3, 0.4, and 0.5 at 1.5 s, the voltage stabilization value is 0.98, 0.96, and 0.94, respectively. The voltage decrease and deviation of the voltage in the DC system are different. The larger the voltage of the load fluctuation, the greater the voltage deviation, and the faster the voltage drop. When there is no robust control effect, the voltage drops rapidly; under

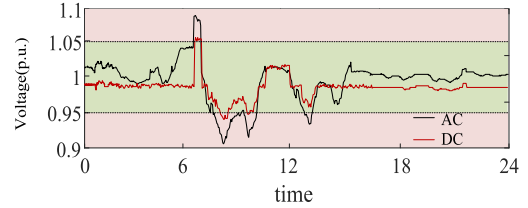


Fig. 14. Voltage situation without robust optimization.

the optimization control of the robust, DC voltage has been significantly improved, but because it only considers the dynamic change of voltage change rate, when the degree of load volatility increases, its DC voltage is increased. The improvement effect is limited. Under the control of robust proposed in this paper, when the degree of load fluctuations increases, the AC power grid and thermal system and hydrogen system provide a certain supporting role to the DC system based on the DC voltage deviation and change rate, and the voltage decreases more gentle. At 1.5 h, the corresponding DC load is removed. By comparison, it can be seen that the DC voltage is improved during the dynamic process of rising.

Figure 16 shows the voltage waveform diagram under different control effects when the distributed power supply in the AC power grid fluctuates. From Figure 16, it can be seen that at the 0.9 h, the photovoltaic forces gradually decreased due to changes in the intensity of the light, and the output of photovoltaic force in the 1.5 h photovoltaic force increased to the rated state. It can be seen from the simulation that under the control of the robust, when the photovoltaic power drops from 0.45 to 0.15 within 1 h, the voltage slowly drops to the stable state value of 0.98, and the maximum voltage changes are 0.379. When the photovoltaic force drops sharply from 0.34 to 0, the voltage

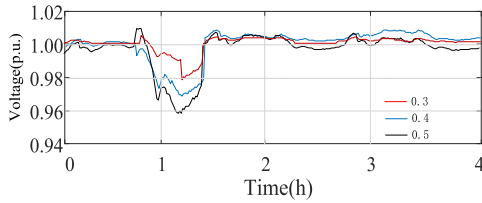


Fig. 15. DC voltage changes waveforms under different control effects.

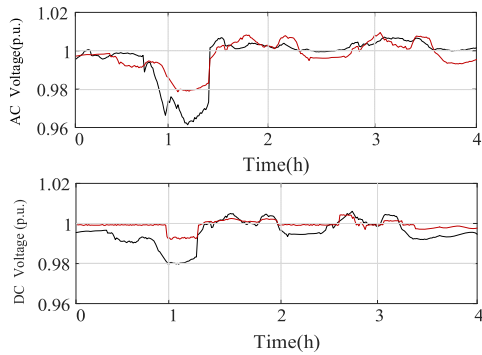


Fig. 16. Voltage changes waveforms under different control effects.

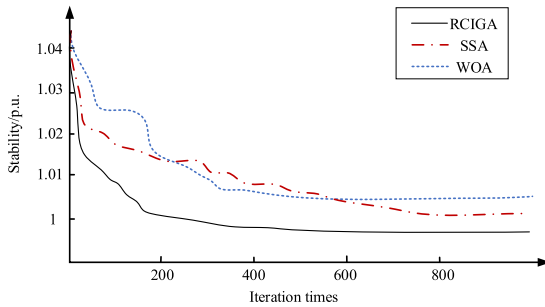


Fig. 17. Convergence of optimization algorithm.

slowly drops to a stable state value of 0.962, and the maximum voltage change rate is 0.402. Under the control of robust optimization, when the photovoltaic power drops from 0.51 to 0.18, the DC voltage reaches the steady state value at 1.5 h, and the maximum voltage changes are 0.361; and when the photovoltaic force drops sharply from 0.51 to 0, the AC voltage slowly decreases, and the AC voltage slowly decreases. At 1.53 h, the steady-state value is reached, and the maximum voltage changes are 0.41; through comparison, it can be seen that the robust control can make the DC voltage further improved when the power fluctuations are large.

The robust control of the improved genetic algorithm (RCIGA) is compared with the sparrow search algorithm (SSA) and whale optimization algorithm (WOA). The results are shown in Figure 17. It can be concluded that the proposed method is superior to other algorithms in terms of optimization accuracy and convergence speed.

Although this paper improves the system voltage stability to a certain extent, the efficiency improvement method adopted in this paper may increase the investment cost. And did not consider the impact on the life of the electrolytic cell. In the next research work, the constraints will be further optimized to reduce operating costs.

7 Conclusion

1. Electric hydrogen production can improve the utilization rate of renewable energy and solve the problem of large fluctuation and strong intermittency of renewable energy. Promote the development and utilization of renewable energy. Improve the stability, flexibility, and renewable energy utilization of the power grid. The simulation results show that the voltage stability of the AC/DC hybrid power grid can be realized by using the proposed method. The maximum fluctuation of DC grid voltage is reduced from 0.9 p.u. to 0.96 p.u. The DC grid voltage is maintained within a safe range.
2. This paper proposes an algorithm for generating the safe and stable boundary of pipe network pressure. Maintain the pressure of hydrogen production and hydrogen storage system within a safe range. When the grid voltage fluctuates, the node pressure of the hydrogen pipe network is adjusted. It can maintain the stability of the grid node voltage. As the MES load capacity increases, the reactive power demand in the system also increases. Adjusting the pipe network pressure can solve the problem of reactive power fluctuation in a short time.
3. The simulation results show that when the output of renewable energy fluctuates, by using the proposed control method, the multi-energy coupling equipment such as electric hydrogen and electric heating can respond quickly, and the maximum fluctuation of AC system voltage is increased by 0.02 p.u. The DC system is improved by 0.016 p.u.

Acknowledgments

This work was supported by the National Key Research and Development Program of China under Grant No. 2017YFB0902100.

References

- 1 Richa M., Prevotet J.C., Dardaillon M., Mroué M., Samhat A.E. (2023) High-level power estimation techniques in embedded systems hardware: an overview, *J. Supercomput.* **79**, 4, 3771–3790.
- 2 Agrawal A., Affijulla S. (2022) A concept for discrimination of electrical fault from cyber attack in smart electric grid, *J. Electr. Eng.* **73**, 4, 299–304.
- 3 Konwar P., Sarkar D. (2022) Strategy for the identification of optimal network distribution through network reconfiguration using graph theory techniques – status and technology review, *J. Electr. Eng. Technol.* **17**, 6, 3263–3274.

- 4 Antalem D.T., Muneer V., Bhattacharya A. (2022) Decentralized control of islanding/grid-connected hybrid DC/AC microgrid using interlinking converters, *Sci. Technol. Energy Transition* **77**, 22.
- 5 Eidiani M. (2022) A new load flow method to assess the static available transfer capability, *J. Electr. Eng. Technol.* **17**, 5, 2693–2701.
- 6 Sanki P., Basu M., Pal P.S., Das D. (2022) Modified power tie-line design for an interconnected microgrid system under restructured AGC scenario, *Arabian J. Sci. Eng.* **47**, 11, 14507–14529.
- 7 Rosli H.M., Mokhlis H., Mansor N.N., Sapari N.M., Halim S. A. (2022) A modified DEP and AHP for load shedding scheme of islanded distribution system incorporating stability index, *J. Electr. Eng. Technol.* **17**, 3, 1581–1592.
- 8 Nettari C., Boubekri A., Benseddik A., Bouhoun S., Daoud D., Badji A., Hasrane I. (2024) Design and performance evaluation of an innovative medium-scale solar dryer with heat recovery based-latent heat storage: experimental and mathematical analysis of tomato drying, *J. Energy Storage* **88**, 111559.
- 9 Xiao H., Pei W., Dong Z., Pu T., Chen N., Kong L. (2018) Reactive power optimization of distributed power distribution network based on global optimization method of metamodel, *Proc. CSEE* **38**, 19, 5751–5762+5931.
- 10 Behzadi M., Askari M.T., Amirahmadi M., Babaeinik M. (2022) Dual identification of multi-complex and non-stationary power quality disturbances using variational mode decomposition in hybrid modern power systems, *Arabian J. Sci. Eng.* **47**, 11, 14389–14409.
- 11 Xu X. (2014) *Modelling, simulation, and energy management research for electricity, gas, and heat based micro energy system*, Tianjin University.
- 12 Liu J., Zhou C., Gao H., Guo Y., Zhu Y. (2018) A day-ahead economic dispatch optimization model of integrated electricity-natural gas system considering hydrogen-gas energy storage system in microgrid, *Power Syst. Technol.* **4201**, 170–179. (in Chinese).
- 13 Li Z., Zhang F., Liang J., Yun Z., Zhang J. (2015) Optimization on microgrid with combined heat and power system, *Proc. CSEE* **3514**, 3569–3576. (in Chinese).
- 14 Javaid S., Li D., Ukil A. (2024) High pass filter based traveling wave method for fault location in VSC-Interfaced HVDC system, *Electr. Power Syst. Res.* **228**, 110004.
- 15 Yang W., Miao S., Liu Z., Han J., Xiong Y. (2024) Control of parallel bidirectional converters under unbalanced conditions in an AC/DC hybrid microgrid, *Electr. Power Syst. Res.* **226**, 109952.
- 16 Sun P., Teng Y., Zhang M., Chen Z. (2021) A novel risk assessment method for hybrid AC/DC system based on transient energy function, *CSEE J. Power Energy Syst.* <https://doi.org/10.17775/CSEEJPES.2021.00860>.
- 17 Suraya S., Irshad S.M., Ramesh G.P., Sujatha P. (2022) Biogeography based optimization algorithm and neural network to optimize place and size of distributed generating system in electrical distribution, *J. Electr. Eng. Technol.* **17**, 3, 1593–1603.
- 18 Yan W., Lei C., Wen X., Wang Q., Li Y., Zhao X., Yu J. (2015) A weak node identification method for reactive power optimization infeasible problems, *Proc. CSEE* **35**, 18, 4616–4624.
- 19 Gümüş T.E., Yalçın M.A., Turan M., Aksoy Tırmıkçı C., Yavuz C. (2021) Steady state voltage stability estimation by using local bus parameters, *J. Electr. Eng. Technol.* **16**, 2, 853–860.
- 20 Ma S., Liu Z., Zheng J., Wu Z., Li N., Guan X., Han J., Yang M., Song Y. (2024) Natural gas hydrate decomposition characteristics at the exploitation anaphase via sediment warming, *Energy & Fuels* **38**, 15, 14334–14342.
- 21 Li H., Zou H. (2022) Short-term wind power prediction based on data reconstruction and improved extreme learning machine, *Arabian J. Sci. Eng.* **47**, 3, 3669–3682.
- 22 Njike Njike I.B., Fotsa Ngaffo F., Tabeu S.B., Kenfack Jitsa A. (2022) Frequency selectivity and enhancement of efficiency in wireless power transfer-based parity-time symmetric trimer, *Arabian J. Sci. Eng.* **47**, 3, 3659–3667.