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Modeling and Coordinated Control of Multi-energy Coupled System with PV-Hydrogen-Energy Storage

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Abstract. Given that the important influence upon the power network of strong randomness and the intermittent features in PV power, this paper is to construct a multi-complementary system, which combines the PV module, electrolysis of water produce hydrogen module, hydrogen fuel cell module and lithium battery energy storage module, all coupling with DC-bus of 800V. It is to build a mathematical model of PV, electrolyzer, hydrogen fuel cell and lithium battery. In this case, it does research on photovoltaic, electrolysis of water producing hydrogen, hydrogen fuel cell power, lithium battery energy storage and other on-grid system and coordinated control strategy. This control strategy not only can make the hybrid system power output controllable, but also can dramatically improve the utilization rate of solar energy and hydrogen energy, which make the usage of clean energy efficient. What's more, this system can smooth the fluctuation of DC-bus's voltage and let it stabilize at 800V and smooth the power of on-grid network. Finally, the simulating result by means of PSCAD/EMTDC tests verifies the efficiency of this hybrid system's coordinated control strategy.

1. Introduction

As the photovoltaic power network permeates more and more nowadays, a great attention should also be paid to its influence upon network's stable and safe operation. Currently, scholars and experts pay high attention to it [1,2]. Hydrogen energy is the most ideal pollution-free and clean energy among the secondary energy. By means of photovoltaic electrolyzer, it is to produce hydrogen when network is at low load. In the peak time, using PEMFC to provide electric energy is one of the efficient methods of improving utilization rate PV power. Nowadays, among them, a hybrid power system of PV-hydrogen-storage coordinated control is one of the popular topics for the scholars and experts both from home and abroad.

Multi-complementary DC micro grid is composed of electrical component models and multi-complementary strategies. It is integrated in system through distributed energy and energy storage equipment, in order to provide thermal energy, electric energy and other energy supply for client. It focuses on the usage of multiple and inter-connected energy, which makes the energy recycle, in order to enhance the energy's efficiency.

Therefore, PV/electrolysis of water/hydrogen fuel cell/lithium battery storage is a whole DC micro grid system, and it is far from simply putting together distributed PV power or distributed wind power and storage section. Currently, it is necessary to do research on how to configure the energy

appropriately and how to do calculation and design required for intelligent coordinated control. The inter-connection of PV panel, electrolyzer, hydrogen fuel cell can make an efficient conversion of solar energy, chemical energy and electric energy. Also, this can solve the problems resulted from high harmonic hazard, uncontrollable trend, flash flicker and others. By means of improving the technique of producing hydrogen from electrolysis of water, all materials and products used in this chemical reaction are very clean and more compatible with national requirement for green energy.

Nowadays, there are many research about models and controls based on the hydrogen storage PV system. Reference [4] joins hydrogen generator and battery storage module into the exchange network point, and this realizes smoothing the active power output of PV power system; reference [5] proposes a mixed on-grid power system which is composed of PV power, PEMFC, battery storage, and super capacitor and utilizes simple control technique to realize power supplying for load and operation on network; reference [6] uses the electrolyzer and fuel cell to storage the hydrogen, which eliminate the problem load fluctuation and intermittent feature by PV power; reference [7], compares and analyzes the features of battery energy storage and hydrogen fuel cell storage based on the fluctuation of PV power, from power generation cost, power capacity to its flexibility; reference [8] proposes a mixed system model and control which is composed of PV power, proton exchange membrane fuel cell, and battery in electric car, whose management and control can realize constant supply of energy; reference [9] proposes PV/wind/fuel cell mixed power system model, whose load control can be realized in simulating software. To summarize, system modeling and research on control of photovoltaic/hydrogen mixed system are still in the early stage, and more profound research is in need.

Confronting the pivotal problems of PV power on grid network's influence upon power network, this paper propose PV on grid power system mixing with hydrogen energy storage, which is composed of electrolyzer, fuel cell and lithium battery, in order to realize active connection and friendly power generation of PV and hydrogen green energy. PV power connects electrolytic hydrogen production, fuel cell, lithium battery energy storage and grid network module with DC busbar to coordinate and control load of all modules, and then satisfies the network by means of controlling the system. Meanwhile, this can maximize the benefit of renewable energy and optimize the operations of each module.

2. Modeling of mixed system

2.1. Model of PV system
The physical essence of PV battery is PN junction. When the PV battery is totally hidden, its feature can be almost expressed by the following ideal diode equation:

$$i_{dk} = n_p I_{sat}(e^{\frac{v_{pvk}}{\eta V_T n_s}} - 1) \tag{1}$$

Where $V_T = k_B T/q_e$ is the thermal voltage of semiconductor material, k_B is Boltzmann constant (usually $1.381 \times 10\text{-}23 \text{J/K}$), T is the absolute temperature, q_e is the unit charge (usually $1.602 \times 10\text{-}19\text{C}$); η is diode quality factor, its value depends on manufacturing technology of PV module and semiconductor; I_{sat} is the reverse saturation current of PN junction; n_s is the serial number of PV module; n_p is the parallel number of PV module; i_{dk} is the steady dark current, which is in strict incremental relationship with output voltage v_{pvk}, and which has nothing to do with light intensity.

i_{gck} is steady state photocurrent, which is more influenced by light intensity, and it equals the output current of PV module when there is short circuit at the output $v_{pvk}=0$. It is in incremental relationship with light intensity, and it can be represented as:

$$i_{gck} = n_p[I_{sc} + \alpha(T - T_{ref})]\frac{S}{S_{ref}} \tag{2}$$

Where I_{sc} is the short circuit current of PV module under the Standard Testing condition (STC), in STC, light intensity is S_{ref}=1000W/m2, battery temperature is T_{ref}=25℃, S is the actual light intensity, α is the temperature coefficient of short circuit current.

Therefore, the actual equivalent model of PV array can be expressed in parallel by an ideal PN junction and a light-control current source, as follows in figure 1:
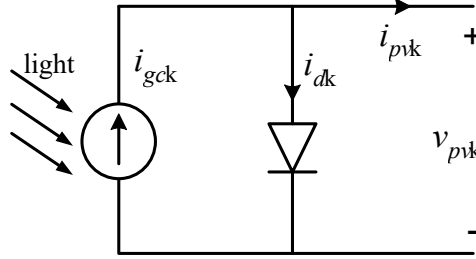

Figure 1. Equivalent model of PV array

Therefore, the relationship of PV array output current i_{pvk} and its output voltage v_{pvk} can be represented as follows:

$$i_{pvk} = n_p[I_{sc} + \alpha(T - T_{ref})]\frac{S}{S_{ref}} - n_p I_{sat}(e^{\frac{v_{pvk}}{\eta V_T n_s}} - 1) \qquad (3)$$

Equation (3) shows the nonlinear relationship between PV array's output current and output voltage under any condition of light intensity and module temperature. PV array can be equivalent to changeable current source, whose output current is nonlinear function of PV array voltage.

$$i_{pvk} = f(v_{pvk}) \qquad (4)$$

The maximum output power of PV array can be expressed as output voltage:

$$P_{pvk} = \max(v_{pvk}i_{pvk}) = \max[v_{pvk}f(v_{pvk})]\big|_{S,T} \qquad (5)$$

Equation (5) shows that the PV array has different maximum power point under different lighting condition. In order to gain maximum output power, each PV array employs individual MPPT control. Equation (4) and (5) show the output characteristic curve of I-V and P-V under different light intensity condition, as is shown in figure 2.

2.2. Electrolyzer model

When PV power is larger than network's demand, extra power will follow central control system's order and be transferred to hydrogen generating device to produce hydrogen. After necessary compression, liquefaction and chemical reaction, this hydrogen will be reserved in storage device.

Under any temperature, alkaline electrolyzer's *U-I* function is shown as follows [10]:

$$U_{cell} = U_{rev} + \frac{r_1 + r_2 T_{el}}{A_{cell}} I_{el}$$
$$+ \left(s_1 + s_2 T_{el} + s_3 T_{el}^2\right)\log\left(\frac{t_1 + t_2 / T_{el} + t_3 / T_{el}^2}{A_{cell}} I_{el} + 1\right) \qquad (6)$$

$$U_{el} = N_{el}U_{cell} \qquad (7)$$

Where N_{el} is the number of batteries connected in series, U_{cell} is electrolyzer's single cell voltage, I_{el} is the current produced in electrolyte, U_{rev} is the reversible battery voltage, which changes slowly with temperature and pressure, r_1, r_2 are electrolyte's Ohmic resistance parameter, s_1, s_2, s_3, t_1, t_2, t_3 are

electrode's overpotential voltage parameters, A_{cell} is electrode's area, and T_{el} is electrolyte's temperature. All parameters are decided by measuring. Electrical features are mainly decided by voltage, current and temperature.

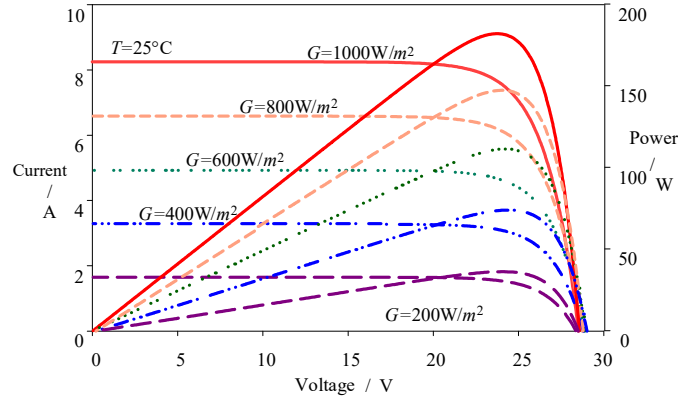Electrolyzer's thermal energy balance equation is as follows:

Figure 2. Characteristic curve of I-V and P-V for Photovoltaic cells under unequal irradiance

$$C_{t\_el}\frac{dT_{el}}{dt} = \dot{Q}_{gen} - \dot{Q}_{el\_loss} - \dot{Q}_{el\_cool} \qquad (8)$$

The volume of hydrogen produced in electrolyzer is as indicated in (9):

$$V_{H_2} = \eta_F\left(T,J\right)\frac{N_{el}I_{el}}{2F} \qquad (9)$$

Where V_{H2} is hydrogen producing rate; T and J are environment temperature and current density; η is their function; F is Faraday constant; I_{el} is EL current.

The hydrogen volume of hydrogen storage tank is:

$$W_{H_2} = \int_{t_1}^{t_2} V_{H_2}dt \qquad (10)$$

Where W_{H2} is volume of hydrogen storage; t_1 are t_2 starting and ending period of producing hydrogen.

$$P_{el}\left(t\right) = P_{el0}e^{-\frac{t}{\tau_{el}}} + P_{el\infty}\left(1 - e^{-\frac{t}{\tau_{el}}}\right) \qquad (11)$$

Where P_{el} is electrolyzer's simulating actual power; P_{el0} is electrolyzer's power at initial state; $P_{el\infty}$ is electrolyzer's power towards the final state; τ_{el} is time constant of electrolyzer's circuit.

2.3. Model of Hydrogen Fuel Cell
FC module is composed of current collector plate, flow field plate, gas diffusion layer, catalytic layer and proton exchange membrane. PEMFC's single cell output voltage is as indicated in (12).

$$U_{fc} = E_{nernst} - U_{act} - U_{ohm} - U_{con} \qquad (12)$$

Where U_{FC} is module's output voltage; U_{nernst} is thermodynamic electromotive force; U_{act} is activation overpotential; U_{ohm} is ohmic overpotential; U_{con} is the concentration overpotential.

According to ideal gas equation of state, the model of PEMFC gas flow is shown in (13).

$$\begin{cases} \dfrac{dp_{H_2}}{dt} = \dfrac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{react} - q_{H_2}^{out}\right) \\[2mm] \dfrac{dp_{O_2}}{dt} = \dfrac{RT}{V_{cn}}\left(q_{O_2}^{in} - q_{O_2}^{react} - q_{O_2}^{out}\right) \end{cases} \tag{13}$$

Where V_{an} and V_{cn} are the volume of anode flow field and cathode flow field of FC module; $q_{H_2}^{in}$ and $q_{O_2}^{in}$ are molar flow of input hydrogen and input oxygen; $q_{H_2}^{react}$ and $q_{O_2}^{react}$ are molar flow of hydrogen and oxygen in reaction; $q_{H_2}^{out}$ and $q_{O_2}^{out}$ are molar flow of output hydrogen and output oxygen.

According the principle of conservation of energy, PEMFC's thermal energy balance equation is indicated in (14).

$$\dot{Q}_{stack} = P_{tot} - P_{fc} - \dot{Q}_{fc\_cool} - \dot{Q}_{fc\_loss} \tag{14}$$

Where Q_{stack} is endothermic power of module, P_{tot} is total power required for the module; P_{elec} is the power of output module; Q_{fc_cool} is thermal power taken away by the cooling water; Q_{fc_loss} is the thermal power that module losses.

2.4. Model of Lithium Battery Energy Storage

Lithium-ion battery, with high specific energy and high specific power together, is characteristic of good recycling capacity, efficiency, large current rate of charging and discharging. Lithium iron phosphate battery is particularly suitable for large-scale of storage in power system. This paper built a new equivalent circuit from the perspective of multi-complementary new energy power grid and its application, which can exactly describe dynamic and static features based on lithium iron phosphate battery. This new equivalent circuit will conduct comprehensive volume forecasting and take many influencing factors into consideration. What's more, it is simple in structure, easy to experiment, etc.

Structure topology of comprehensive new equivalent circuit is as follows:

Circuit on the left of figure 3 is to describe the time feature of battery operation, its essence is to decide battery's SoC (ration of available remaining capacity and maximum capacity). Capacity is battery's available capacity, I_{batt} is battery's operation current. The voltage of Capacity is equal to SoC in numerical value. SoC is the final output of left side circuit. Right side circuit is the typical resistant capacity model, which is to describe the dynamic I-V feature in battery operation, and it is called voltage response model. V_{oc} is the open circuit voltage under SoC's control; R_{series} represents the sum of electrolyte in battery, electrode, current collector and other ohmic internal resistance. R_{cyc} is recycling resistant, which shows that the ohmic internal resistance increases as the battery recycles. Two RC circuit links are to describe long and short time constant's response under the step excitation, which are correspond to electrochemical polarization of electrolyte battery and concentration polarization; V_{batt} is the equivalent circuit's terminal voltage, which is the final output of the model.
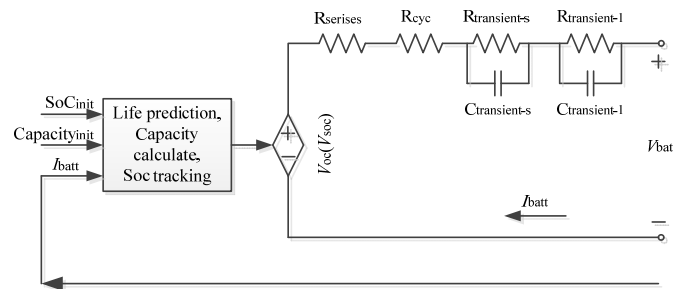

Figure 3. Comprehensive equivalent circuit model of lithium-ion battery

The above circuit parameters are all non-constant value. Theoretically they are the functions of relevant factors, such as SoC, recycling times, temperature, etc. The actual modeling process can simplify some factors while focusing on some other main factors. Equation (15) is a mathematical model of hybrid circuit based the state of V_{tran-s} and V_{tran-l} in two RC circuit links.

$$\begin{cases} \dfrac{dV_{tran-s}}{dt} = -\dfrac{V_{tran-s}}{R_{tran-s}C_{tran-s}} + \dfrac{I_{batt}}{C_{tran-s}} \\ \dfrac{dV_{tran-l}}{dt} = -\dfrac{V_{tran-l}}{R_{tran-l}C_{tran-l}} + \dfrac{I_{batt}}{C_{tran-l}} \end{cases} \qquad (15)$$

$$V_{batt} = V_{oc} - V_{tran-s} - V_{tran-l} - I_{batt}(R_{cyc} + R_{series})$$

In the actual modeling process, and according to the actual function of left circuit, it is often to use *SoC*'s calculation, in order to reduce the complexity of model. In (16), SoC_{init} shows battery's initial state of charge, C_{use} is battery's available capacity. The *SoC* evaluation method is called Current Integration Method.

$$SoC = SoC_{init} - \int_{t_0}^{t} I_{batt} / C_{use} dt \qquad (16)$$

Original model's available capacity C_{use} is taken as constant, which is very different with the actual situation. C_{use} is not only related to storage environment and recycle situation, but also closely related to charging and discharging condition of battery.

3. Coordinated control strategy

The whole structure of active multi-complementary system based on photo-hydrogen storage is indicated as figure 4. It shows that PV, electrolyzer, PEMFC and lithium energy storage are all collected by DC-BUS. It is transferred to public power network by DC/AC grid-connected inverter. According to the features of *I-U*, *P-U* and MPPT, its control equation is indicated in (17).
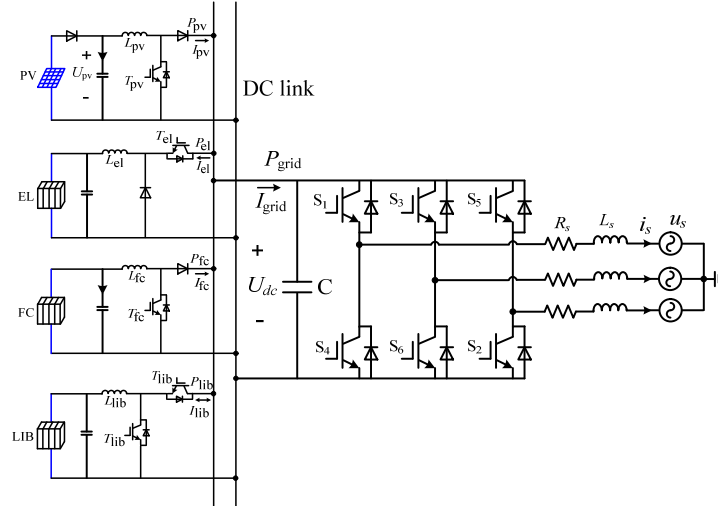

Figure 4. The architecture diagram of multi-energy coupled system

$$m_{PV} = \left(k_{ppv} + \frac{k_{ipv}}{s} \right)(U_{MPP} - U_{PV}) \qquad (17)$$

DC-BUS voltage dynamic equation is shown as follow:

$$C\frac{dU_{dc}}{dt} = I_{PV} + I_{fc} \pm I_{lib} - I_{el} - I_{grid} \qquad (18)$$

Electrolyzer and PEMFC control equation is shown as follow:

$$\begin{cases} m_{el} = \left(k_{pel} + \dfrac{k_{iel}}{s} \right) \Big[\left(P_{PV} - P_{grid} \right) - P_{el} \Big] & P_{PV} > P_{grid} \\[4mm] m_{fc} = \left(k_{pfc} + \dfrac{k_{ifc}}{s} \right) \Big[\left(P_{grid} - P_{PV} \right) - P_{el} \Big] & P_{PV} < P_{grid} \end{cases} \tag{19}$$

Multi-complementary hybrid system power equation is shown as follow:

$$P_{grid} = P_{PV} + P_{fc} \pm P_{lib} - P_{el} \tag{20}$$

The principles of multi-complementary hybrid system coordinated control are shown in figure 5. This coordinated control block diagram can realize real time coordinated distribution of hybrid system power towards each module. Under the collaboration of EL module, LIB module and FC module, it is to balance hybrid system's remaining power and power shortage. By means of adjusting the volume of consumption power of electrolyzer, it is thereby to ensure that LIB's terminal voltage will operate between the maximum value and minimum value (PV module's output is 0 in cloudy and raining day. Reducing the load can make sure that LIB's terminal voltage operates within the safe range).
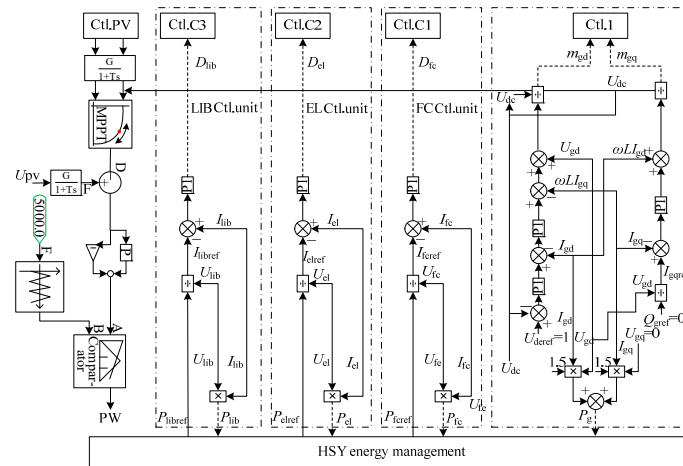

Figure 5. Diagram of multi-energy coupled system coordinated control

The control principle of each module in hybrid system:

PV module employs voltage loop control to realize the optimal power output. PV array output current I_{pv} is produced by light intensity G, environment temperature T, and PV's terminal voltage U_{pv}. L_{pv} is PV equivalent inductance; U_{pv_mppt} is the output voltage required for producing the optimal power; D_{pv} is the control signal of Boost converter.

Lithium-ion battery LIB module employs current loop control to realize consumption/supplement of hybrid system for remaining power/power shortage. P_{bus} is system's active power imbalance; U_{lib_min} and U_{lib_max} are the minimum value of super capacitor discharge depth voltage and maximum voltage of charging depth. U_{lib} and I_{lib} are SC terminal current and current; P_{lib_ref} and I_{lib_ref} are reference power and reference current.

El module employs current loop control to realize the reasonable consumption of electrolyzer for hybrid system's remaining power. U_{el} and I_{el} are EL terminal voltage and inductor current; P_{el_ref} and I_{el_ref} are reference power and reference current; D_{el} is the control signal of Buck converter.

FC module employs current loop control. HYS energy management center produces reference power P_{fc_ref}, and it is divided by FC terminal voltage U_{fc}, and thereby get the reference current i_{fc_ref}. PI controller, by means of error of i_{fc_ref} and i_{fc}, is to produce control signal D_{fc}.

Grid-connected module D axis employs double loop control, voltage outer loop and current inner loop, in order to guarantee that the DC-BUS's voltage stabilizes at 800V; q axis employs current single loop control to realize reactive power 0, quick and stable tracking. I_d, I_q and e_d, e_q are dq axis's current and voltage; ω and θ are electrical angular velocity and phase-locked loop angle; U_{dcref} and U_{dc} are DC-BUS's reference voltage and its actual value.

Control center system, through signal flow, examines, coordinates and controls hybrid system's operation situation. Therefore, there are stable network's power, good quality of voltage and electric energy and low light rejection ration. System power monitoring strategy is shown in figure 6.
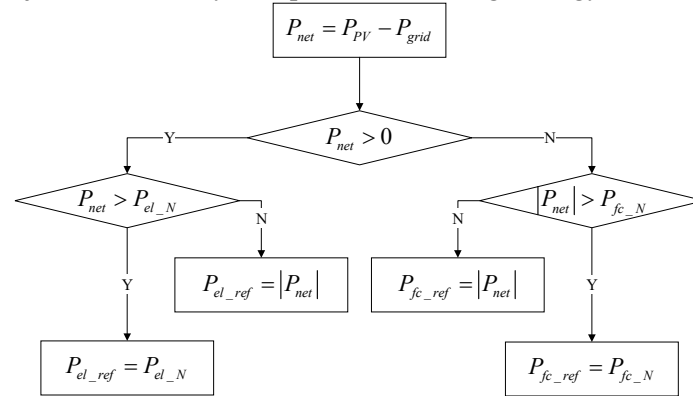
$$P_{net} = P_{PV} - P_{grid}$$

$$P_{net} > 0$$

$$P_{net} > P_{el\_N}$$

$$|P_{net}| > P_{fc\_N}$$

$$P_{el\_ref} = |P_{net}|$$

$$P_{fc\_ref} = |P_{net}|$$

$$P_{el\_ref} = P_{el\_N}$$

$$P_{fc\_ref} = P_{fc\_N}$$

Figure 6. System power monitoring strategy

The analysis shows that the unbalanced power P_{net} of the system controls the operation state of the electrolyzer and PEMFC, and the power control of the system is also constrained by the electrolyzer P_{el_N} and constant power $PEMFC_{fc\_N}$.

4. Simulation and analysis

Building hybrid and grid-connected system of PV/hydrogen producing/hydrogen fuel cell/lithium battery in PSCAD/EMTDC. System's main parameters are in Table 1.

Table 1. Parameters of EL unit.

Parameter	Value	Parameter	Value
r_1	7.3e-5	r_2	-1.1e-7
s_1	1.6e-1	s_2	1.38e-3
s_3	-1.6e-5	t_1	1.60e-2
t_2	-1.3	t_3	4.12e2
A	0.25	a_1	99.5%
a_2	-9.58	a_3	-0.056
a_4	1502.7	a_5	-70.8
N_{el}	21	T_{el}	25

Simulation condition 1: PV output (P_{pv}=0.26MW) and fuel cell (P_{fc}=0.1MW) are always larger than sum of line side load demand (P_g=0.1MW) and EL (P_{el}=0.1MW) consumption power. At this moment, system's remaining active power is $P_{bus}=P_{pv}+P_{fc}-P_g-P_{el}$=0.16MW, LIB reacts quickly to absorb system's remaining active power P_{bus}, LIB is in charging state, and at this moment, LIB absorbs system's remaining active power $P_{lib}=P_{bus}$, as the charing time of LIB increases, its terminal voltage U_{lib} (0.4kV) keeps increasing, when simulation reaches 2s moment, $U_{lib}=U_{lib\_max}$ (0.5kV), at this moment, LIB quits the operation. EL consumption system power increases to $P_{el}=P_{pv}+P_{fc}-P_g$(0.26M W). The result of simulation is shown as follows:
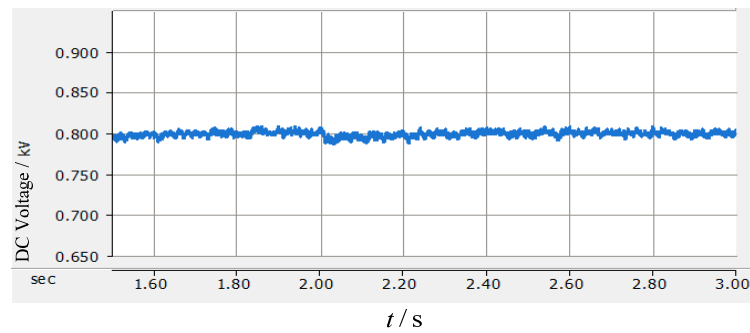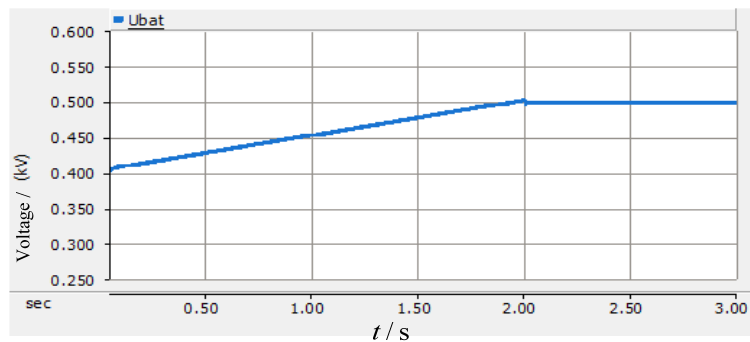
Figure 7. DC-link voltage
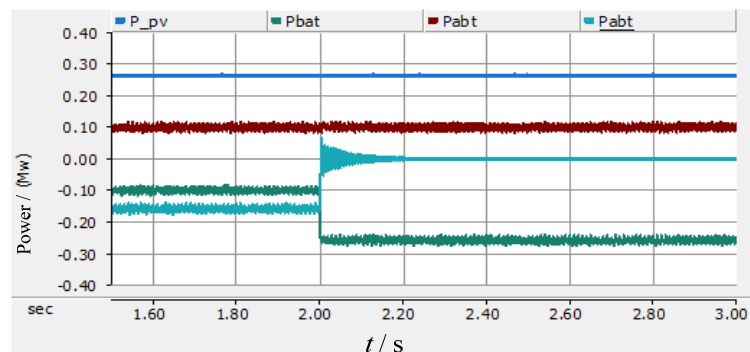

Figure 8. Terminal voltage of lithium-ion battery

Figure 9. The output power of PV, EL, FC, LiB

Simulation condition 2: Lithium-ion battering directly side connects the inverter controlled by VF. VF control's reference voltage 0.38kV, frequency 50Hz, AC-BUS connects to the inverter controlled by VF, connecting to load 1 between 0-1s, power is 90kW; connecting to load 2 at 1s, power is 100kW, By connecting to load 2, it is to test and verify the discharging result of lithium-ion battery and VF inverter's controlling effect.

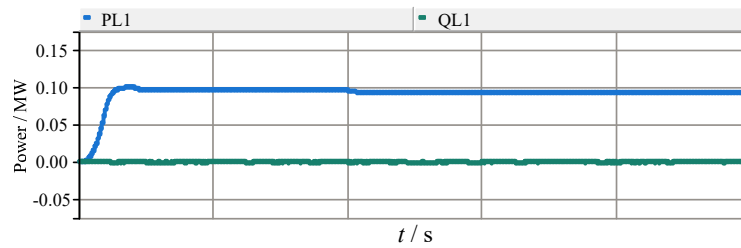Figure 10. The output active and reactive power of lithium-ion battery

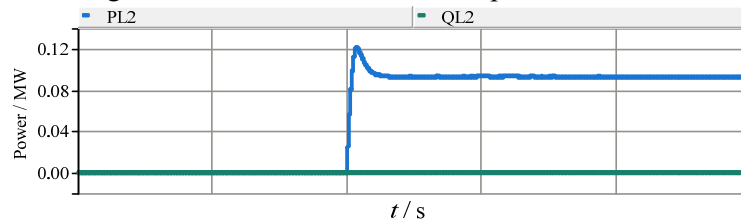Figure 11. The active and reactive power of load 1

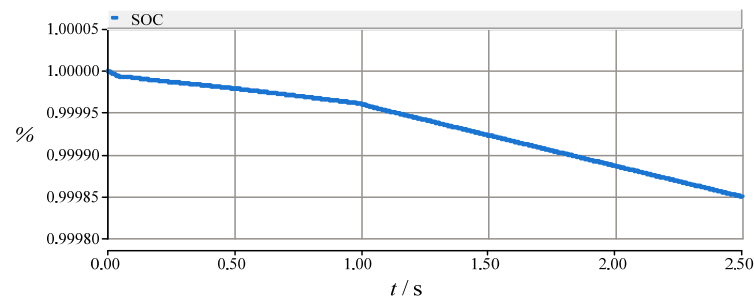Figure 12. The active and reactive power of load 2

Figure 13. The SoC of lithium-ion battery

According to figure 10-13, after connecting to load 1 and load 2 respectively, and by means of inverter controlled by VF, lithium-ion energy storage can quickly track and smooth system's power fluctuation, and keep system's voltage and frequency stable, and thus guarantee the quality of electric energy.

5. Conclusion
The result of simulation leads to the following conclusion:

1) The coordinated control strategy proposed in this paper can make PV power system's output controllable and its network power stable. The DC-BUS's voltage can be stabilized at 800V.

2) By means of coordination collaboration of PV module, EL module, FC module and LIB module in energy management system, LIB can charge and discharge in safe way under three conditions of PV output fluctuation. FC can control its power output according to the production of hydrogen. El can quickly operate and quit according to the situation.

3) Compared with PV module single grid-connected power, multi-complementary hybrid power system increases PV utilization and hydrogen energy utilization, which are totally compatible with the requirement of green energy development.

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