The Power Coordinated Control of Hybrid Energy Storage System with Hydrogen Energy

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Abstract. With the increase of new energy permeability, photovoltaic power generation is widely used, but because of its own volatility and intermittent, it will lead to uncontrollable power generation and large fluctuation of grid-connected power. Hydrogen energy is a green and efficient way of energy storage. Hybrid energy storage system combined with super-capacitor can better realize photovoltaic grid-connected. This paper established a photo-hydrogen-supercapacitor hybrid energy storage system, contained electrolyzer, fuel cells and supercapacitor, and proposed a power coordination control strategy which ensure that the DC bus voltage is stable when PV is excessive or insufficient output or not worked on the rainy days or nights. Simulation proves the effectiveness of this system, and the maximum utilization of solar energy resources is realized.

1. Introduction
Photovoltaic power generation is a double-edged sword. Its advantage is that it can use solar energy to generate electricity, but its disadvantage is that the grid-connected power fluctuates greatly, which seriously affects the power quality. Coordination with the energy storage unit can effectively solve the above problems. Due to the current advocated promotion of “green development”, hydrogen storage is one of the ideal energy storage unit options. When the amount of power generation is excessive, hydrogen can be produced by the electrolytic cell, and when the amount of power generation is insufficient, the hydrogen produced by the electrolysis can be used for the proton exchange membrane fuel cell to emit electric energy. Hydrogen combustion is clean and pollution-free, which is in line with the green development concept[1].

The literature[2] combines energy storage and power storage, and establishes a hybrid energy storage system of supercapacitor and battery based on energy transformation model, which not only reduces the DC/AC converters number, but also maintains the voltage of DC bus steady. However, the use of the battery is not clean enough. The literature[3] adds a fuel cell to the battery-supercapacitor as an auxiliary device to provide energy in the dynamic response of the system, so that it can be used as a backup power source when the output of renewable energy is insufficient, but the article ignores energy use of the surplus of renewable energy output. The literature [4] combines photovoltaic power generation with fuel cell power generation, and proposes a hydrogen-photovoltaic combined power supply system based on a dual-input Buck converter, which utilizes the output power of the solar battery as much as possible. However, only electrolyzed water is mentioned in this article, and it is not
detailed and simulated. The literature[5] uses electrolytic cells and fuel cells, and proposes a hydrogen energy storage management algorithm to solve the power fluctuation and intermittent problems of photovoltaic power generation. However, when the hydrogen is insufficient or excessive, the system cannot supply or dissipate the power normally. The literature[6] proposes a control strategy for power generation of a hybrid systems of photo-voltaic, wind turbine, fuel cell, and supercapacitor, which ensures that the difference that cell and supercapacitor can be absorbed/supplemented between PV and wind turbine output and load.

For improving the photovoltaic absorptive capacity of system and consider the use of clean energy, a hybrid energy storage system of photovoltaic, electrolytic cell, fuel cell and supercapacitor is established. The power coordination control strategy is proposed to ensure that PV output is excessive/insufficient and the DC bus voltage is stable in rainy days or nights. The validity of the control method is proved by simulation, and the maximum utilization of solar energy resources is realized.

2. Integrated framework of hybrid energy storage system
The framework of the mixed grid-connected power generation system proposed in the paper is shown in the figure1. The main parts of the system include photovoltaic array, electrolyzer, proton exchange membrane fuel cell, super-capacitor and converter. Each unit is linked to DC bus in parallel through DC converter, and connected to the power grid through the inverters.

![Figure 1. Hybrid energy storage system framework](image)

The photovoltaic array realizes the real-time transmission of photovoltaic output to DC bus with the change of illumination intensity through maximum power point tracking technology. When the power is excess, the electrolyzer electrolyze water to producing hydrogen, absorbs excess power, and stores the hydrogen for the use of fuel cell. When the power is insufficient, fuel cells burn hydrogen to generate electricity and supply to system. Supercapacitors can absorb and release electric energy. The combination of supercapacitors and hydrogen energy storage can better ensure that the output of hybrid energy storage system controllable, power injected into DC-AC grid-connected unit is smooth, the DC bus voltage is stable, and the photovoltaic permeability is improved.

3. Brief description of system unit models

3.1. Photovoltaic unit
Photovoltaic cells are the basic unit for converting solar energy into electric energy. The photovoltaic array is composed of a series of photovoltaic cells in series and parallel. In this paper, an equivalent model considering both accuracy and practicability is used to describe the dynamic characteristics of photovoltaic cell. The voltage-ampere characteristics of photovoltaic cells are expressed as follows[7]:

$$I_{pq} = \frac{G}{G_{ref}} \left[ N_v I_{sc} - \mu (I_b - T_{ref}) \right] \cdot \left( 1 - \frac{I_b}{I_{sc}} \right) \cdot \exp \left( -\frac{U_b}{A U_{sc}} \right) \cdot N_v I_{sc} \left[ \exp \left( \frac{U_{pq} - dU_{pq}}{A U_{sc} N_s} \right) - 1 \right]$$  (1)
\[
T_h = T_a + t_c G \\
A_h = \frac{U_a}{10 \left(1 - \frac{I_a}{I_{oc}}\right)} \\
dU_{vc} = \varepsilon (T_h - T_{ref}) - R_a \left[ -\mu \frac{G}{G_{ref}} (T_h - T_{ref}) + \left(\frac{G}{G_{ref}} - 1\right) \cdot N_p I_{oc} \right]
\]

In the above formula, \(I_{pv}\) is the output current of PV, \(U_{pv}\) is the output voltage of PV, \(G\) represents the solar illumination intensity, \(G_{ref}\) represents the reference illumination intensity, \(N_p\) represents the parallel number of PV array modules, \(N_s\) represents a series number of photovoltaic array modules, \(U_{oc}\), \(I_{oc}\) severally represents the open-circuit voltage and short-circuit current in photovoltaic modules, \(T_h\) represents the ambient temperature, \(T_{ref}\) represents the reference temperature, \(t_c\) represents the temperature variation coefficient of photovoltaic module, \(T_b\) represents the surface temperature of photovoltaic array cells at the illumination intensity \(G\) and ambient temperature \(T_e\). Temperature variation coefficients of current and voltage under reference illumination intensity for \(\mu\) and \(\varepsilon\) respectively. \(U_m\), \(I_m\) severally represents voltage and current at maximum power points of photovoltaic cells. \(R_a\) represents series resistors of photovoltaic modules.

In this paper, disturbance observation method is used to realize MPPT control of photovoltaic cells.

3.2. Electrolyzer unit
The basic principle of proton exchange membrane water electrolyzer(PEMWE) is that water is decomposed into hydrogen and oxygen by electricity. It is mainly composed of a thin layer of proton exchange membrane electrolyte, catalytic electrode, collector and so on[8]. Its U-I equation is:

\[
U_{cell} = E_{rev} + \frac{R_1 + R_2}{A_{el}} I_{el} + \left(a_1 + a_2 t_{el} + a_3 t_{el}^2 \right) \cdot 10 \left(\frac{b_1 + b_2}{A_{el}} + \frac{b_2}{t_{el}} \right) I_{el} + 1
\]

In the above formula, \(U_{cell}\) is the cell voltage of the cell, \(E_{rev}\) is the reversible cell voltage which changes slowly with temperature and pressure, \(t_{el}\) represents the effective area of the cell, \(I_{el}\) represents the DC current of the cell, \(R_1\) and \(R_2\) represents the ohmic resistance parameters of the electrolyte, \(a_1, a_2, a_3, b_1, b_2, b_3\) severally represents the related parameters of the electrode overvoltage.

Output voltage of electrolyzer: \(U_{el} = N_{el} U_{cell}\), \(N_{el}\) represents the number of batteries in series for the electrolytic cell.

The dynamic power equation of EL:

\[
P_{el(t)} = P_{el(0)} e^{-\frac{t}{\tau_{el}}} + P_{el(0)} \left(1 - e^{-\frac{t}{\tau_{el}}}\right)
\]

In the above formula, \(P_{el}\) is the actual dynamic output power of electrolyzer, \(P_{el(0)}\) is the initial state EL power output, \(P_{el(t)}\) is the final state EL power output, \(\tau_{el}\) is the dynamic time constant of EL.

The rate of hydrogen production:

\[
F_{Hy, prod} = \eta(T, J) \frac{N_{el} I_{el}}{2F}
\]

In the above formula, \(T\) is the ambient temperature, \(J\) is the current density, \(\eta\) is the function of both, \(F\) is the Faraday constant, its value is 96485 c/mol.
3.3. Fuel cell unit
The PEMFC stack is composed of several single cells in series. A single cell consists of cathode, anode and proton exchange membrane between cathode and anode. The anode supplies hydrogen and the cathode supplies air[9].

The voltage equation is: 

\[ U_{fc} = E_{nernst} - V_{act} - V_{conc} - V_{ohm} \]  

(6)

In the above formula, \( U_{fc} \) is the output voltage of a single cell in a fuel cell, \( E_{nernst} \) is the thermodynamic electromotive force, \( V_{act} \) is the activation overvoltage, \( V_{conc} \) is the concentration difference overvoltage, \( V_{ohm} \) is the ohmic overvoltage.

The stack voltage of FC is:

\[ U_{stack} = N_{fc} U_{fc} \]

(7)

In the above formula, \( P_{fc} \) is the actual dynamic output power of electrolyzer, \( P_{fc0} \) is the initial state FC power output, \( P_{fcx} \) is the final state FC power output, \( \tau_{fc} \) is the dynamic time constant of FC.

Hydrogen Consumption Rate of Fuel Cells:

\[ Q_{H2,fc} = \frac{N_{fc} P_{fc}}{V_{stack}ZF}, \]

where \( Z \) is electrodes number and \( F \) is the Faraday constant.

3.4. Supercapacitor Unit
SC is also called electrochemical double-layer capacitor. The equation between the energy absorbed and released by SC and its voltage is as follows.

\[ W = \frac{\beta}{\alpha} C_{sc} \left[ (\alpha U_0)^2 - (\alpha U_f)^2 \right] = \alpha \beta C_{sc} \left( U_0^2 - U_f^2 \right) \]  

(8)

In the above formula, \( W \) is the energy absorbed/released by supercapacitors. \( C_{sc} \) is the single capacitor of supercapacitor. \( U_0 \) and \( U_f \) are the initial and state voltages of supercapacitors, respectively. \( \alpha, \beta \) severally represents series and parallel numbers of supercapacitors.

The equivalent capacitance of a supercapacitor bank is \( C_N = \frac{\beta}{\alpha} C_{sc} \). The equivalent total internal resistance of supercapacitors is \( r_N = \frac{\alpha}{\beta} r_{sc} \), among them, \( r_{sc} \) is the unit resistance of supercapacitor.

4. System power coordination control strategy
Power coordinated control is the core of system design. The so-called system power coordinated control refers to the rational power distribution of multi-terminal complex system composed of photovoltaic array, electrolyzer, fuel cell, supercapacitor, grid load and converter. For photovoltaic power generation system under grid-connected mode, the basic principle of power coordinated control is to utilize solar energy resources as much as possible and meet the power demand of grid load on the premise of guaranteeing the safe working of energy storage devices.

In this energy storage system, the energy density of hydrogen is higher than that of supercapacitors. So the starting priority of hydrogen storage equipment should be higher than that of supercapacitors. In the actual operation process, when the photovoltaic output is inconsistent with the user load, the electrolytic cell or fuel cell will start first to balance the DC bus power. Supercapacitors are coordinated with hydrogen energy storage because they need to absorb/release electricity. So after a
period of start-up of hydrogen energy storage device, supercapacitors will start in time to maintain DC bus power balance. Considering that supercapacitors have upper and lower voltage limits, after exceeding their voltage limits, they inopera and the system continue to work by hydrogen storage.

From the practical point of view, this paper will analyze the following three situations: photovoltaic output is larger than load demand, photovoltaic output is slightly smaller than load demand because of its or load fluctuation, and photovoltaic output is not available in rainy days or nights.

**Working condition 1:** When the photovoltaic output is greater than the load, since the starting priority of the hydrogen storage device should be higher than that of the supercapacitor, the electrolyzer is preferentially activated, and it electrolyzes water and absorbs too much electric energy to generate hydrogen. Supercapacitors do not produce electricity themselves, so if they want to release electrical energy, they must first absorb the energy. After a period of time, the supercapacitor is activated, which absorbs excess energy for storage. However, the supercapacitor itself has an upper voltage limit. When the absorbed electric energy reaches the upper voltage limit, it can no longer continue to work. At this time, the SC exits the work, and the electrolyzer power is increased to absorb the remaining energy.

**Working condition 2:** Due to the fluctuation of PV output or load demand, the PV output will be slightly less than the load demand in a certain period of time. However, frequent start and stop of the electrolyzer will have a great impact on the life of the electrolyzer, which will greatly increase maintenance costs. Therefore, at this time, EL is not stopped, but the output power is adjusted, and the fuel cell and the super capacitor are coordinated to achieve stable power and the DC bus voltage. When it is slightly smaller than the load demand, the starting priority of hydrogen energy storage equipment should be higher than that of SC to start fuel cells. Because SC needs to release electric energy to maintain balance and can provide sufficient storage space for energy absorption, after a period of time, SC starts and releases energy, but SC itself has a lower voltage limit, when the released electric energy reaches the lower voltage limit, it can not continue to work. At this time, SC withdraws from work, which will reduce the power of electrolyzer, in order to maintain power balance.

**Work condition 3:** When the photovoltaic power is not available on rainy days or nights, EL should be withdrawn from work at this time. Fuel cells should be activated to release electricity for load demand. Due to the excessive power shortage, SC should also be started in time to provide the required power to the load together with fuel cells. However, SC itself has a lower voltage limit. When the released electric energy reaches the lower voltage limit, it can’t continue to work. At this time, SC withdraws from work. In order to balance the power of the system, load is reduced step by step. When the photovoltaic power is still output but far less than the load demand, the electrolytic cell should also be withdrawn from the work, the follow-up work is similar to the third condition, so no more analysis.

**5. Simulation and analysis**

Based on PSCAD/EMTDC software simulation platform, this paper establishes a hybrid power generation system model. The main parameters of the simulation system are as follows: DC bus voltage 800V, three-phase voltage 380V, frequency 50Hz, filter reactance of three-phase inverters 0.005H, equivalent resistance 0.005Ω, supercapacitor capacitor 1.5F, SC voltage upper limit 0.5kV, SC voltage lower limit 0.3kV, the switching frequency of the converter 2000 Hz.

**Working condition 1:** When the photovoltaic output is 0.36MW, the load demand $P_g = 0.1$MW, and the photovoltaic output is greater than the load demand. EL starts first, and its absorption power $P_{el} = 0.1$MW. At this time, the remaining power of the system $P_{bus} = P_{PV} - P_{el} - P_{g} = 0.16$MW. At this time, the supercapacitor starts quickly, absorbs the surplus power $P_{sc} = P_{bus} = 0.16$MW, and the SC is in charge state. With the increase of SC charging time, its terminal voltage $U_{sc}$ (0.4kV) keeps rising. When the simulation runs to 2s, $U_{sc} = U_{sc-max}$ (0.5kV), then SC withdraws from operation. At this time, the residual power of EL absorption system increases to $P_{el} = P_{PV} - P_{g} = 0.26$MW.
The figure 2 shows the waveform of the voltage at both ends of the EL and SC. From the figure, it can be seen that the voltage of the EL changes abruptly at 2s, and the slope is larger after 2s because the power of EL increases. SC is increasing from 0.4KV. When it absorbs electric energy to 2S, it reaches the upper limit of 0.5KV. At this time, it no longer works and the voltage remains unchanged.

![Figure 2. EL, SC voltage waveform](image)

The figure 3 reveals the power comparison of PV, EL, SC and DC bus voltage waveform. The PV power is 0.36MW. At 2s, the EL power increases from 0.1MW to 0.26MW. The power of SC before 2S is 0.16MW. At 2s, the power drops out because of the upper limit of voltage, and then becomes 0MW. When PV output is greater than the load demand, the discharge coordination between EL and SC is realized through coordinated control, and the DC bus voltage is stabilized by maximizing the use of electric energy. DC bus voltage waveform is on the right.

![Figure 3. PV, EL, SC power and DC bus voltage waveform](image)

Working condition 2: Because of fluctuation of photovoltaic output or load demand, photovoltaic output will be slightly smaller than load demand in a certain period of time. When the photovoltaic output $P_{PV} = 0.26$MW, the load demand $P_g = 0.32$MW, and the photovoltaic output is slightly smaller than the load demand. Because frequent start-up and shut-down of electrolyzer will have a great impact on the life of it, so the electrolyzer continue to work $P_{el} = 0.2$MW. At this time, the fuel cell starts first, and its power $P_{fc} = 0.1$MW, lack of power in the system $P_{Bus} = P_{PV} - P_{el} - P_g + P_{fc} = 0.16$MW. At this time, SC starts quickly, releases its own stored electric energy, $P_{sc} = P_{Bus} = 0.16$MW, the SC is in discharge state. With the increase of SC discharge time, the terminal voltage decreases continuously. When the simulation runs to 2s, $U_{sc} = U_{sc\_min} (0.3kV)$, when SC inoperates, EL reduces its own power and absorbs the residual power, and the power decreases to $P_{el} = P_{PV} - P_g + P_{fc} = 0.04$MW.

The figure 4 shows the waveform of the voltage at both ends of the EL and SC. The voltage of the EL changes abruptly at 2S, and the slope before 2S is obviously larger, because the power of EL varies greatly. SC voltage decreases continuously. When it releases electric energy to 2S, it reaches the lower limit of 0.3KV. At this time, it no longer works and the voltage remains unchanged.
The figure 5 shows the power comparison of PV, EL, SC and DC bus voltage waveform. The photovoltaic power is 0.26MW. At 2s, the EL power is increased from 0.2MW to 0.04MW, the FC power is always 0.1MW, the SC power is 0.16MW before 2s, and then the power is changed to 0MW because of the lower voltage limit. When PV output is slightly less than the load demand, EL, FC and SC achieve their charging and discharging coordination through coordinated control, maximize the use of electricity and stabilize the voltage. The DC bus voltage waveform is on the right.

Work condition 3: When PV is not available on rainy days or nights, EL should be withdrawn from work at this time. Fuel cells should be activated to release electricity for load demand. The PV output is 0 MW, EL shuts down, the load demand $P_f = 0.3$MW, the fuel cell starts first, and the power shortage of the system $P_{bus} = P_f - P_{fc} = 0.2$MW. At this time, SC starts quickly, releases its own stored electric energy, $P_{sc} = P_{bus} = 0.2$MW, SC is in discharge state. With the increase of SC discharge time, the terminal voltage decreases continuously. When the simulation runs to 2s, $U_{sc} = U_{sc-min} (0.3$kV), when SC inoperable, in order to balance the power of the system, the load is reduced step by step.

Figure 6 is the waveform of SC voltage and FC,SC power. SC voltage decreases continuously. When it releases electric energy to 2S, it reaches the lower limit of 0.3kV. At this time, it no longer works and the voltage remains unchanged. FC power fluctuates after 2S due to load reduction. SC power is 0.2MW before 2s. When 2s, it withdraws from operation due to the lower voltage limit, and then the power becomes 0MW. When rainy days or nights, photovoltaic can not output, FC and SC
through coordinated control, with step-by-step load reduction, maximize the use of electricity, stabilize the DC bus voltage.

**Figure 7.** DC bus voltage and load active and reactive power waveform

Figure 7 reveals the DC bus voltage and the charge active and reactive power change waveform. DC bus voltage will fluctuate after 2S due to load reduction step by step, but it will remain stable after 2S coordinated by the energy storage unit. Load is reduced step by step after 2S to maintain voltage stability.

Under three conditions, through the power coordinated control of EL, FC, SC, can realize the maximum use of electricity and play a more stable bus voltage, equipoise the power of this system.

6. Conclusion
Based on the hybrid energy storage system of photovoltaic array, electrolyzer, fuel cells and supercapacitor, each unit model is built in PSCAD/EMTDC. According to three operating conditions of this hybrid system, a reasonable control strategy is proposed. Under the premise of satisfying the constraints of system and the stability of DC bus voltage, the reliable load supply and the maximum utilization of solar energy resources are realized. The simulation results show that the model can achieve the desired effect under the proposed control strategy.

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