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System Modeling of Wind-PV-ES Hybrid Power System and Its Joint Scheduling Research

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Abstract: In recent years, the technology of wind power, photovoltaic power and storage battery power is becoming increasingly mature. However, because of the randomness, intermittent and instability of wind and solar energy, the model of Wind-PV-ES hybrid power will become highly competitive. This paper analyzes three kinds of generation models and combines with the technology of battery storage to calculate and model the system in one example, which contributes to the establishment of a small model of Wind-PV-ES hybrid power system. Based on the MATLAB simulation platform, the feasibility of this model can be verified.
Keywords: Wind-PV-ES hybrid power, system modeling, example analysis

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1. INTRODUCTION

Nowadays, a great deal of research has been focused on renewable energy, with the problem of excessive consumption of non-renewable energy, increasing cost of fossil fuels, limited storage capacity and increasingly serious environmental pollution. As inexhaustibly new energies, wind and solar power have received the general attention of researchers [1-2]. At present, the technology of wind power and photovoltaic power generation is gradually mature and has wide commercial value. The form of its utilization is mainly divided into two kinds: grid-connected and off-grid. Grid-connected system is often inserted in high voltage transmission network centrally and massively, and then transmits electricity to the load center remotely. Off-grid system is often inserted in distribution network in a distributed manner, transmitting electricity locally [2]. As the main utilizing form of new energy sources, wind and solar power are obviously intermittent and fairly random, A large scale grid may bring great impact to power grid in Wind-PV-ES hybrid power system [3]. At this point, making reasonable use of energy storage battery technology can increase the reliability and stability of Wind-PV-ES hybrid power system to some degree. But energy storage equipment is high-cost and short-life [9-10], so how to reasonably allocate the capacity and the proportion is a vital subject, which makes the power grid run economically and reliably.

This paper researches wind power and photovoltaic power generation partly from several aspects, including system structure, output model, characteristic curve [4-9], etc. The research analyzes an entity case in Gusu, Suzhou where the power and energy are calculated based on the data of local actual wind speed and light intensity. Then, a small-size Wind-PV-ES hybrid power model is simulated by MATLAB, which can be verified feasible.

2. OPERATION MODEL OF WIND-PV-ES HYBRID POWER UNIT

2.1 System structure

The basic structure of Wind-PV-ES Hybrid Power System is shown in figure 1, it is mainly composed of wind power generator set, photovoltaic power generator set and battery energy storage system. Wind power generator set and Photovoltaic generator set are alternative renewable energy subsystems; storage battery is the device of energy storage; all three are directly connected to DC Bus, then through DC/AC inverter and transformer connected to AC bus.

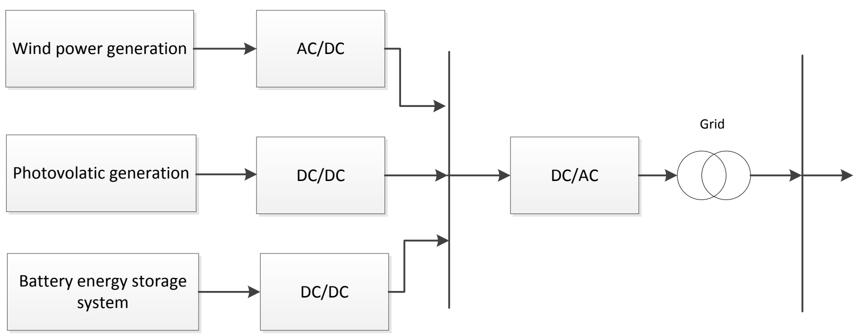

Fig.1 The basic structure of Wind-PV-ES Hybrid Power System

2.2 Output model of wind power generator set

Wind power generation is a kind of power-generating approach that uses wind power to rotate the generator to produce electricity. Wind power generation actually realized energy conversion twice. The first is to turn primary energy into mechanical energy and the second is to turn mechanical energy into electric energy.

Wind power generator set is composed of wind rotor, generator, electric energy extraction system, guidance system, yaw system, converter, controller, etc. Its principle is to turn kinetic energy of wind into rotary mechanical energy, and then drive the generator rotor rotate, eventually conductors separate the magnetic lines to achieve power generation.

Output model of wind power generator set is greatly affected by surface rough degree and supporting height, there are differences between actual wind speed and wind speed of monitoring site, so the actual wind speed should be changed into:

$$V(t) = V_g[L/L_g]^{\alpha} \tag{1}$$

Where V(t)and V_g are wind speed of monitoring site and actual wind speed at t respectively. L and L_g are height of hub and measured height respectively. α is descriptive factor of surface rough degree and the value is related to the surface environment of erection site(generally range from 0.14 to 0.25).

Actual power of wind power generator set is also affected by wind speed. The power is 0 while actual wind speed is less than starting speed or more than maximum operating speed.

Mathematical relationships are as follows:

$$P(t) = \begin{cases} 0 & V(t) < V_{min} \text{ or } V(t) > V_{max} \\ P_N & V_N \ll V(t) \ll V_{max} \\ P_N \frac{V(t)^2 - V_{min}{}^2}{V_N^2 - V_{min}{}^2} & V_{min} \ll V(t) \ll V_N \end{cases} \tag{2}$$

Where P(t) is power of Wind power generator set at t. P_N is rated power. V_{min}, V_{max} and V_N are minimum starting wind speed, maximum wind speed and minimum rated wind speed of Wind power generator set respectively.

2.3 Output Model of Photovoltaic Generator Set

According to Electrical Engineering, an equivalent circuit of photovoltaic panels based on single diode model could be established.

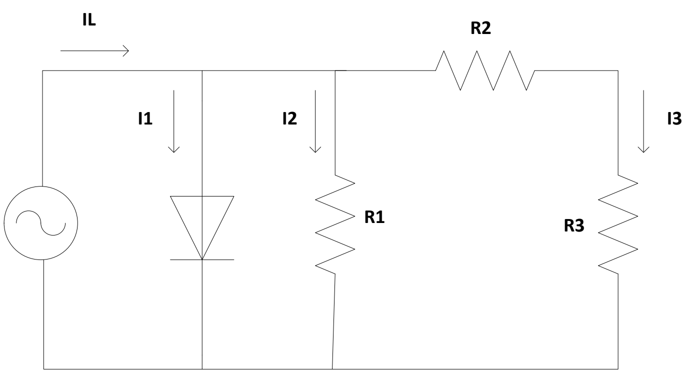

Fig.2 Equivalent circuit of photovoltaic battery

$$I_L = I_1 + I_2 + I_3 \tag{3}$$

It is a formula according to Kirchhoff's current law(KCL).

In the equation, $I_1 = I_0\left[\exp\frac{q(U+I_3R_2)}{AKT} - 1\right]; I_2 = \frac{U+I_3R_2}{R_1}$, among which I_L is photo-generated current; I_3 is output current; U is output voltage; I_1 is current flowing through the diode; R_2 is series resistance equivalent to photovoltaic battery; R_1 is parallel resistance equivalent to photovoltaic battery; k is Boltzman constant; T is absolute temperature; N is the constant of P-N junction curve.

Therefore, the mathematical expression of photovoltaic battery model should be:

$$I_3 = I_L - I_0\left[\exp\frac{q(U+I_3R_2)}{AKT} - 1\right] - \frac{U+I_3R_2}{R_1} \tag{4}$$

On the one hand, formula (3) is not very practical in engineering calculation cases. On the other, photovoltaic battery suppliers usually provide technical parameters such as short-circuit current (I_d), open-circuit voltage (U_0), load current of maximum power point (I_{max}), load voltage of maximum power point (U_{max}). Hence, parameters given above can implement the simplify of formula (3) which comes out to be a mathematical model suitable for engineering calculation:

$$I_3 = I_d\left[1 - C_1\left[exp\frac{U}{C_2U_0} - 1\right]\right] \tag{5}$$

Where variable $C_1 = \left(1 - \frac{I_{max}}{I_d}\right)exp\left(1 - \frac{U_{max}}{C_2U_0}\right); C_2 = \left(\frac{U_{max}}{U_O} - 1\right)\left[\ln\left(1 - \frac{I_{max}}{I_d}\right)\right]^{-1}$

To illustrate the output characteristics of photovoltaic batteries, characteristic curves like I-U and P-U are mostly used. Theoretically, photovoltaic effect serves as the foundation of solar battery generation. As a non-linear output, the power is neither a constant circuit source nor a constant voltage source. Under a certain temperate and sunlight intensity, characteristic curves of I-U and P-U can be illustrated as Fig.3. Starting from scratch, the access resistance R keeps increasing, which brings the output voltage Vph similar tendency; when R comes to a certain value, the output power has a sharply decrease and gradually reduces to zero. There is a maximum of output power during this process, which can be defined as Pm under the specific temperature and sunlight intensity.

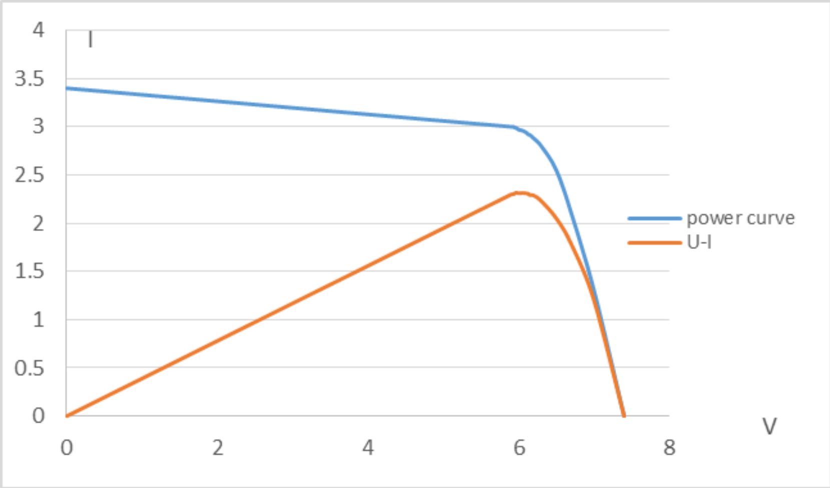

Fig.3 Characteristic curve of photovoltaic battery

A number of small units constitute photovoltaic battery packs in series or in parallel. Tandem combination can boost the maximum DC voltage of solar power system, while parallel combination can boost the maximum DC current of solar power system. Therefore, DC voltage or current can be changed by accessing series packs or parallel packs to acquire the optimum value. After that, the output characteristic equation of photovoltaic model can be given as follow:

$$I = n_p I_{LG} - n_p I_{OS}\{\exp\left[\frac{q}{n_s ASK(V+IRs)}\right] - 1\} \tag{6}$$

Where, n_p and n_s stand for the number of parallel or series photovoltaic batteries respectively.

2.4 Battery energy storage system

To improve the schedulability of the system, the battery energy storage system cuts the peak and fills the valley by comparing the consumption of load and output of wind-solar generation system. Battery stores excess energy at the valley of the load and releases the stored energy at the peak of the load. At the same time, it makes the output of wind-solar generation system more stable. Of course, it demands battery energy storage system with large power and capacity to realize the control target.

It is necessary to take into account the size of the battery capacity, temperature and other factors when establishing a model of battery.

The output model is:

$$\mathrm{E} = N_c^{sy} E_0 - \frac{KSOC}{SOC - N_c^{sy} Q_N \int_0^t i(\tau) d\tau} + Aexp\left(-B \int_0^t i(\tau) d\tau + C_\lambda\right)$$
$$SOC = \frac{N_c^{sy} N_b^{sy} Q_N - \int_0^t i(\tau)}{N_c^{sy} N_b^{sy} Q_N} \times 100\% \tag{7}$$
$$C_p = C_\lambda (T_B - 25)$$

Where E is defined as the battery electromotive force. E_0 is initial electromotive force . K is polarization voltage constant. A is the weighting factor of battery voltage variations. B is the weighting factor of battery capacity change. Q_N is the Rated capacity of battery . SOC is the battery's state of charge, that is, the percentage of the remaining power in the battery. C_λ is the Polarization effect coefficient. T_B is the temperature of battery energy storage system. N_c^{sy} and N_b^{sy} are number of batteries in series and parallel respectively.

During the operation of the system, SOC of the battery energy storage system changes with the change of the power consumption of load and the output of wind-solar generation system, which includes charging state, discharge state and static state. The running state of battery energy storage system at time t depends on the output power of wind-solar hybrid generation system at time t, stored power of battery energy storage system at time t-1 and the power consumption of load at time t. The mathematical model of battery's characteristics reflects the change of the stored energy.

Condition of charging state is:

$$[W_{wind}(t) + W_{pv}(t)] \times \eta_{inverter} - Q_l(t) > 0$$
$$Q_b(t-1) < Q_{bmax} \tag{8}$$

Stored energy in charging operation state:

$$Q_b(t) = Q_b(t-1) \times (1 - \delta_{put})$$
$$+\{[W_{wind}(t) + W_{pv}(t)] \times \eta_{inv} - E_l(t)\} \times \eta_{in}, \quad Q_b(t-1) < Q_{bmax} \tag{9}$$
$$Q_b(t) = Q_{bmax}, Q_b(t) \geq Q_{bmax}$$

Where $Q_b(t)$ is Stored energy of battery at time t. δ_{put} is the discharge rate of battery per hour. $W_{wind}(t)$ is the output power of Wind generator at time t. $W_{pv}(t)$ is the output power of photovoltaic generator at time t. η_{inv} is the efficiency of inverter. $Q_l(t)$ is the power consumption of load at the time t. η_{in} is the charging efficiency of battery. Q_{bmax} is the maximum storage capacity of battery.

Condition of discharge state is:

$$[W_{wind}(t) + W_{pv}(t)] \times \eta_{inv} - Q_l(t) < 0$$
$$Q_b(t-1) > Q_{bmin} \tag{10}$$

Stored energy in discharge operation state:

$$Q_b(t) = Q_b(t-1) \times (1 - \delta_{put})$$
$$+\{[W_{wind}(t) + W_{pv}(t)] \times \eta_{inv} - E_l(t)\}/\eta_{put}, \quad Q_b(t) > Q_{bmin} \tag{11}$$
$$Q_b(t) = Q_{bmin}, Q_b(t) \le Q_{bmin}$$

Where η_{put} is the discharge efficiency of battery. Q_{bmin} is the minimum storage capacity of battery.

Minimum storage capacity of some batteries is decided by maximum depth of discharge:

$$Q_{bmin} = (1 - DOD) \times Q_{bmax} \tag{12}$$

Stationary state of batteries refers to the state, neither discharge nor charging, when generating capacity equals to power consumption of load, batteries discharge to Q_{bmin} but grid system still lacks of power or charge to Q_{bmax} but grid system still has surplus power batteries will all in stationary state.

3. EXAMPLE ANALYSIS

3.1 Basic data

With the help of MATLAB simulation software, the capacity of generating units is optimized in Gusu, Suzhou, Jiangsu Province, China. Firstly, meteorological data of typical years in Gusu area is selected, including annual wind speed curve (Fig.4) and annual light intensity curve (Fig.5).

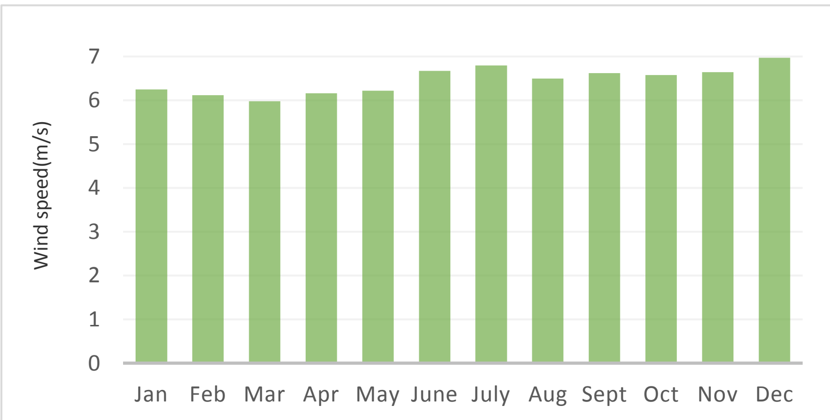

Fig.4 Annual wind speed curve

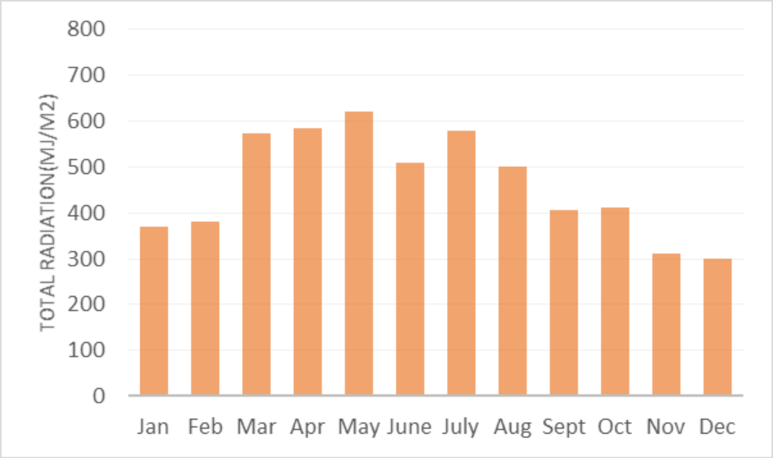

Fig.5 Annual light intensity curve

In the process of optimization calculation, scheduled total output of storage battery is 40MW. Initial capacity of battery accounts for 60%. The rated power of wind turbine, photovoltaic module and battery pack is respectively set to 2MW, 280KW and 30MWh.

3.2 Optimization results

Based on the unit output model and constraint condition established in the paper, optimal allocation ratio of Wind-PV generator set (Tab.1) and SOC annual state diagram of storage battery (Fig.6) can be built by genetic particle swarm optimization.

Tab.1 Optimal allocation ratio of Wind-PV generator set

Month	P_v(KW/m^2)	P_w(KW/unit)	W_{total}(KWh)	W_{user}(KWh)
Jan	16.94	34.12	13056.00	13817
Feb	18.10	31.80	13056.00	11268
Mar	25.88	31.44	15974.40	17783
Apr	27.13	32.77	16709.76	19379
May	30.32	33.01	17980.80	16195
June	25.32	36.13	16659.84	13957
July	26.34	40.71	17930.88	18263
Aug	24.15	35.37	16064.64	15076
Sept	19.68	33.01	13895.04	19084
Oct	20.52	30.61	13756.80	12905
Nov	15.28	31.08	11834.88	16309
Dec	14.49	44.55	14117.76	12713

The wind speed of this place is relatively stable, whose monthly average is between 6 m/s and 7m/s, so the monthly wind generation output has little fluctuation. However, the monthly photovoltaic generation output fluctuates obviously due to the influence of different temperature and irradiance. The photovoltaic curve turns out to be a parabola, reaching the maximum in May. The wind speed curve rises unstably, reaching the maximum in December. At the same time, the wind speed and irradiance are strong in summer, so the output of wind power and photovoltaic generation, which can be stored, is relatively rich.

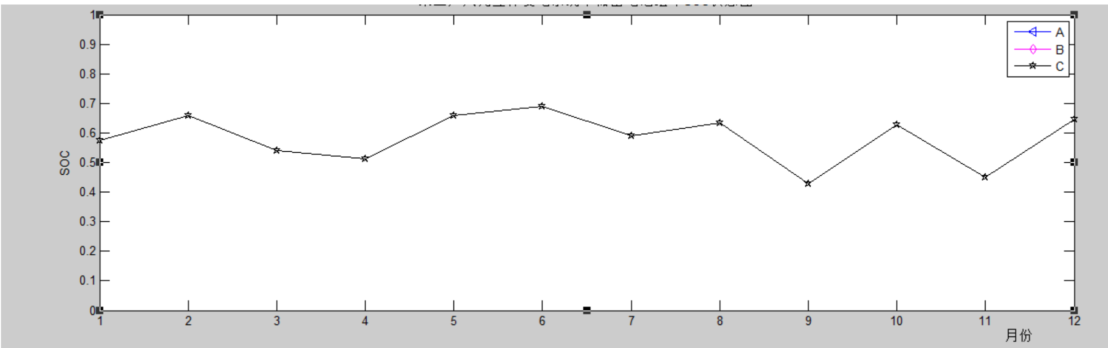

Fig.6 Annual SOC state diagram of storage battery

The life-span of the battery has a great relationship with depth of discharge (DOD). In a certain extent, the greater the DOD is, the shorter the battery life will be. However, during the design, the value of DOD should not be too small. For the reason that the smaller the value is, the greater the remaining of the storage will be, which not only brings about the waste of resource, but also increases the cost of the system. Based on this, SOC of storage battery in the example is limited to 30%~90%. Besides, the initial capacity of battery pack is set at 60 percent of the rated capacity during charging and discharging. The figure above shows that the value of SOC in the calculation fluctuates range from 45% to 70%, which proves that the configuration of the example is reasonable.

4. SUMMARY

In this paper, through modeling and simulation, the equipment capacity of Wind-PV-ES power generation unit is reasonably configured to make it have the ability of constant output. Meanwhile, it proves that the energy storage system can both improve the output of combined generation system of wind and photovoltaic and stabilize the fluctuation of output power. The battery's energy storage system can be used to realize the economic optimization of the whole system. Then use the maximum power limit strategy to ensure energy storage work in a reasonable and safe condition, so as to protect the energy storage device, but also to meet the electricity demand.

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