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The Application of Fuzzy Technology to Hybrid Photovoltaic-wind Renewable Energy Sources

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Abstract: - Renewable energy, such as solar energy and wind energy are desirable for power generation due to their unlimited existence and environmental friendly nature. However the non-linearity characteristic of photovoltaic-wind and the high initial investment impede its wide commercialization. This paper proposes the application of fuzzy technology to fuzzy charging management and system DC output control. All these are accomplished in several cheap embedded control circuit based on MCU. Compared with previously proposed approaches, this method is much more efficient and cost-effective and yet exhibits excellent performance.

Key-Words: - Fuzzy technology, Numerical-fuzzy approach, PID, Hybrid photovoltaic-wind system, MCU

1 Introduction

Renewable energy, such as solar energy and wind energy are desirable for power generation due to their unlimited existence and environmental friendly nature. More and more modern ideas [1] and new techniques [2] are being used in the exploitation of solar power and wind energy [3] along with the developing of green energy conception. We realize in practice it is difficult to utilize natural resources all weather for the separate solar power or wind energy system because of the constraint of time and section. Hybrid photovoltaic-wind power system which synthesizes the strong complementarities of solar power and wind energy in time and region is a sort of rational energy system [4].

Fuzzy control as a sort of new control idea which has strong adaptability and best robustness is good for photovoltaic-wind power system which contains many indetermination quantities and is difficult to describe with precise mathematical model. The disquisition provide a fuzzy charging management based on expert information, which establish the relation equitably between lead-acid battery state and charging parameter, and guaranty the storage battery life in photovoltaic-wind power system validly. At the same time, the system combines fuzzy theory with the traditional PID control to adjust the DC output. Fuzzy / PID control not only has simple control structure, strong robustness and high reliability but also wane the overshoot and expedite the response time. It has a favorable control effect on the hybrid photovoltaic-wind energy system which has delay in time and uncertain in model structure and parameters.

2 Fuzzy Charging Management Based on Expert Information

2.1 Dual-level Three States Charging Approach

Because of the variety of environments to which the photovoltaic-wind power system are installed, a dual-level three states charging module are established, which not only take full advantage of nature energy but also prolong the lead-acid battery service life by rationalizing the charging process. The dual-level, one is over standard open-circuit voltage (Voc), the other is precise floating charge voltage （Vf）. Three states are expounded as follows. Dual-level Three States Charging schematic diagram can refer to figure 1 [5]. (The chart only shows the charging process at a fixed temperature.)

The first stage：When the lead-acid battery voltage is less than the standard open-circuit voltage, photovoltaic-wind power system will charge the storage battery at its available maximum current which is different from the system power, and the maximum current is limited no more than C/5 which is defined as the maximum charging rate (here C is the accumulator capacity) [6], at the same time the maximum current will vary at a certain range for the environment changefully. That is the first state high current bulk charge state, and the system will keep the bulk charge until the battery voltage reach Voc then enter the next state. In this state, the charge degree can get 70%-90%.

The second stage： Constant over standard open-circuit voltage charge state is the second stage, in this stage, the battery will be charged at constant over standard open-circuit voltage (Voc), until the charge rate down to Ioct, and then enter the next stage. According to the characteristic of monomer lead-acid battery, when the charge capacity climbs up to about 95%, the voltage across of monomer battery will boost abruptly. This stage will guarantee the full charging among the battery of a sort. At the same time, the exorbitant standard open-circuit voltage will augment exhaust gas, so the choice of standard open-circuit voltage (Voc) is very important, and it varies based on the environment temperature. In this state, the charge degree can get almost 100%.

The third stage: Floating charge state will charge the battery at constant precise floating charge voltage （Vf）. This stage also can maintain the voltage lest the battery discharge spontaneously. The choice of Vf is significant to the battery life for even the 5% error will halve the battery life and it also correlate with the environment temperature.

During the dual-level three states charge, the temperature is also a key factor, which influences the whole course of charging. To charge the battery well in a large range of environment temperature, it is necessary to change the value of dual-level according to the environment because lead-acid battery has negative temperature coefficient about 4mv/℃. For every given lead-acid battery type, establish the correspondence input-output data pairs for fuzzy charging management based on reference data which is acquired from large number of assays and expert record which obtain from the manufacturer.

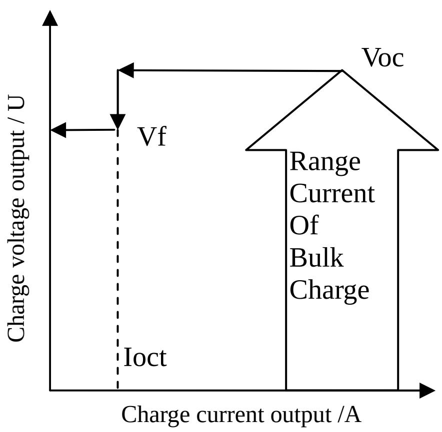

Fig.1 A dual-level three states charge

2.2 Fuzzy System Foundation [7, 8]

We can get a set of desired input-output data pairs, such as:

$$(A_1^{(1)}, A_2^{(1)}, A_3^{(1)}; B_1^{(1)}), (A_1^{(2)}, A_2^{(2)}, A_3^{(2)}; B_1^{(2)}), \ldots \qquad (1)$$

Where A_1, A_2 and A_3 are inputs, and B_1 is the output. The task here is to generate a set of fuzzy rules from the desired input-output pairs of (1), and use these fuzzy rules to determine a mapping $f:\ (A_1, A_2, A_3) \rightarrow B_1$.

Step 1: Divide the input and output spaces into fuzzy regions

Here simplify the import to A_1, A_2 and A_3, where A_1 express the storage battery voltage, A_2 express the charge current and A_3 express the storage temperature. In the same way, the output simplify to B_1, which express the Battery charge voltage.

① The domain intervals of A_1 is [0, Vmax] (divided by Vmax, the [0, Vmax] will become [0, 1]), where “domain interval” of a variable means that most probably this variable will lie in this interval (the values of a variable are allowed to lie outside its domain interval). Here we define A_1^j （j=1,2,…,15）as complete fuzzy sets, and choose quadrangle membership functions $u_{A_1^j}(x_i)$ as follow:

A_1^1 And A_1^{15} adopt trapezoidal membership functions, such as:

$$u_{A_1^j}(x_i) = u_{A_1^j}(x_i; a_1^j, b_1^j, c_1^j, d_1^j)$$

$$= \max\left\{\min\left\{\frac{x_i - a_1^j}{b_1^j - a_1^j}, 1, \frac{d_1^j - x_i}{d_1^j - c_1^j}\right\}, 0\right\}$$

The membership functions of A_1^1:

$u_{A_1^1}(x_i; -\infty, 0, 0.25, 0.3)$

The membership functions of A_1^{15}:

$u_{A_1^{15}}(x_i; 0.9, 0.95, 1, \infty)$

The membership functions of A_1^2 , …, A_1^{14} are Gaussian membership functions:

$$u_{A_1^j} = u_{A_1^j}(x_i; \delta, c_j) = e^{\frac{(x_i - c_j)^2}{2\delta^2}}$$

Here $\delta = 0.02$ j=2,3,⋯,14 $c_j = 0.2 + 0.05 \times j$.

② The domain intervals of A_2 which express the charge current is [0, Imax] (divided by Imax, the [0, Imax] will become [0, 1]).

Here we define A_2^j (j=1,2,…,21) as complete fuzzy sets, and choose Gaussian membership functions $u_{A_2^j}(x_i)$ as follow:

$$u_{A_2^j} = u_{A_2^j}(x_i;\delta,c_j) = e^{-\frac{(x_i-c_j)^2}{2\delta^2}}$$

Here $\delta = 0.02$ $c_j = 0.05 \times (j-1)$ j=1,2,⋯,21.

③ The domain intervals of A_3 which express the storage temperature is [0, Tmax] (divided by Tmax, the [0, Tmax] will become [0, 1]).

Here we define A_3^j (j=1,2,…,10) as complete fuzzy sets, and choose quadrangle membership functions $u_{A_3^j}(x_i)$ as follow:

$$u_{A_3^j}(x_i) = u_{A_3^j}(x_i; a_3^j, b_3^j, c_3^j, d_3^j)$$
$$= \max\left\{\min\left\{\frac{x_i - a_3^j}{b_3^j - a_3^j}, 1, \frac{d_3^j - x_i}{d_3^j - c_3^j}\right\}, 0\right\}$$

Here $d_3^j = c_3^j + 0.05 = b_3^j + 0.1 = a_3^j + 0.15$, j=1, 2… 10 and $a_3^1 = -\infty$ $b_3^1 = 0$ $c_3^{10} = 0.95$

④ In the fuzzy charging management based on dual-level three states charge, we simplify the output to B_1, which express the Battery charge voltage. For the dual-level of over standard open-circuit voltage (Voc) and floating charge voltage (Vf) which have to be exact, here choose fractionized Gaussian membership functions. The domain intervals of B_1 is [0, Vmax] (divided by Vmax, the [0, Vmax] will become [0, 1]).

Here we define B_1^j (j=1,2,…,41) as complete fuzzy sets, and choose Gaussian membership functions $u_{B_1^j}(x_i)$ as follow:

$$u_{B_1^j} = u_{B_1^j}(x_i;\delta,c_j) = e^{-\frac{(x_i-c_j)^2}{2\delta^2}}$$

Here $\delta = 0.02$ $c_j = 0.025 \times (j-1)$ j=1,2,⋯,41.

Step 2: Generate fuzzy rule from a given data pairs

We suppose N pairs of input-output data, such as $(x_{01}^p, x_{02}^p, x_{03}^p; y_0^p)$, here $p = 1, 2, \cdots, N$.

For every input-output data pairs, we ascertain the grade of membership for x_{0i}^p (i=1, 2, 3) ,which subject to fuzzy set A_i^j ,so as y_0^p. Choose the fuzzy set which is the maximum grade of membership to compose fuzzy rules. Suppose these fuzzy sets are $(A_1^{j^*}, A_2^{j^*}, A_3^{j^*}; B_1^{j^*})$, and the fuzzy rule is:

$$if\ \ x_1 \in A_1^{j^*} and\ x_2 \in A_2^{j^*} and\ x_3 \in A_3^{j^*},\ then\ y = B_1^{j^*}$$

Step 3: Establish a degree to each rule

Since there are usually lots of data pairs from reference data and expert record, and each data pairs generates one rule, it is highly probable that there will be some conflicting rules, i.e., rules that have the same IF part but a different THEN part. Assigning a degree (D) to each rule generated from data pairs $(x_{01}^p, x_{02}^p, x_{03}^p; y_0^p)$, and we accept only the rule from a conflict group that has maximum degree.

$$D = \prod_{i=1}^{3} u_{A_i^{j^*}}(x_{0i}^p) u_{B_1^{j^*}}(y_0^p) u^p \quad \ldots\ldots (2)$$

Here u^p is the reliability level parameter of experience credibility.

$$u^p = \begin{cases} 1 & \text{The normal data} \\ 2 & \text{The key data} \end{cases} \quad \ldots\ldots (3)$$

For the normal input-output data pairs, the reliability level parameter take 1, while for the key point the parameter is doubled. So the rules have the same IF part, we accept the rule that has maximum degree to compose the fuzzy rule base.

Step 4: Create and supplement a combined fuzzy rule base

The principle of composing the fuzzy rule base:

① The fuzzy rules which do not conflict with the other rules are deduced from step 2.

② Choose the rules that have maximum degree when there have conflicts in the fuzzy rule base.

③ The rules are made of the data pairs which come from reference data and expert record.

④ Only the rules which get from normal test conditions are insufficient, so it is necessary to complete the fuzzy rule base by supplementing some rules, such as the rules of the charging condition at abnormal temperature, and the rules of the charging condition when storage battery is leaking, etc.

Step 5: Establish fuzzy system

The fuzzy system adopt product inference engine, singleton fuzzifiers and center average defuzzifier.

Here l is the fuzzy rule, and $\bar{y}^l$ is the center of out fuzzy set $B_1^{j^*}$ for fuzzy rule l.

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When the sensor detect input, the fuzzy system fuzzify the input, and ascertain the output of dual-level three states charge which also serve as the real time charge output voltage of DC/DC module Buck-Boost circuit according to equation 4. The output voltage is controlled by fuzzy intelligence management which regulates the value by driving MOSFET to adjust duty ratio. The part of Fuzzy Charging Management Based on Expert Information can see in figure 2.

$$f(x)=\frac{\sum_{l=1}^{m}\bar{y}^{l}\left(\prod_{i=1}^{3}u_{A_i^l}(x_i)\right)}{\sum_{l=1}^{m}\left(\prod_{i=1}^{3}u_{A_i^l}(x_i)\right)} \quad \ldots\ldots (4)$$

3 Fuzzy Control Based on PID

3.1 Fuzzy/PID System

In photovoltaic-wind complementation power system, adopt fuzzy / PID which combine the fuzzy theory and traditional PID to control the output DC voltage. That means, utilize fuzzy reasoning to adjustment factor within large deviation range, while switch to PID within small deviation, and the transition is automated implementation by the given deviation range. This part can refer to the corresponding component in Fig.2 photovoltaic-wind complementation power supply system fuzzy control chart. In the chart, storage batteries (Ⅱ) are at floating charge state, and its DC output will supply the DC load and DC-AC inverter, the system given voltage target is the voltage which is required by DC load and DC-AC inverter input voltage, the voltage difference (VD) is the difference between the real time voltage of DC load or inverter input and system given voltage target, the voltage variance ratio (Rate) is the real time voltage variance ratio of DC load and DC-AC inverter input, the output of fuzzy/PID control is the valve controller (Valve) for voltage and current which adjust the duty ratio of Buck-Boost converter and control the current sink of discharger.

3.2 Fuzzy/PID System Foundation

The input and output variable of fuzzy/PID controller system are simplified as: the input voltage difference (VD), the input voltage variance ratio (Rate), the output valve controller (Valve) for voltage and current which adjust the duty ratio of Buck-Boost converter and control the current sink of discharger.

Input fuzzy variable: the voltage difference (VD) is the difference between the real time voltage of DC load or inverter input and system given voltage target. For the given storage batteries, the normalization coordinate is [-1, 1], and the fuzzy subsets of membership functions are {low, okay, high}, which choose Gaussian membership functions as follow:

$$u_{high}=u(x;\delta_h,c_h)=e^{-\frac{(x-c_h)^2}{2\delta_h^2}}$$

here δ_h =0.3， c_h =-1；

$$u_{low}=u(x;\delta_l,c_l)=e^{-\frac{(x-c_l)^2}{2\delta_l^2}}$$

here δ_l =0.3， c_l =1；

$$u_{okay}=u(x;\delta_o,c_o)=e^{-\frac{(x-c_o)^2}{2\delta_o^2}}$$

here δ_o =0.3， c_o =0.

Input fuzzy variable: the voltage variance ratio (Rate) is the real time voltage variance ratio of DC load and DC-AC inverter input. For the given storage batteries, the normalization coordinate is

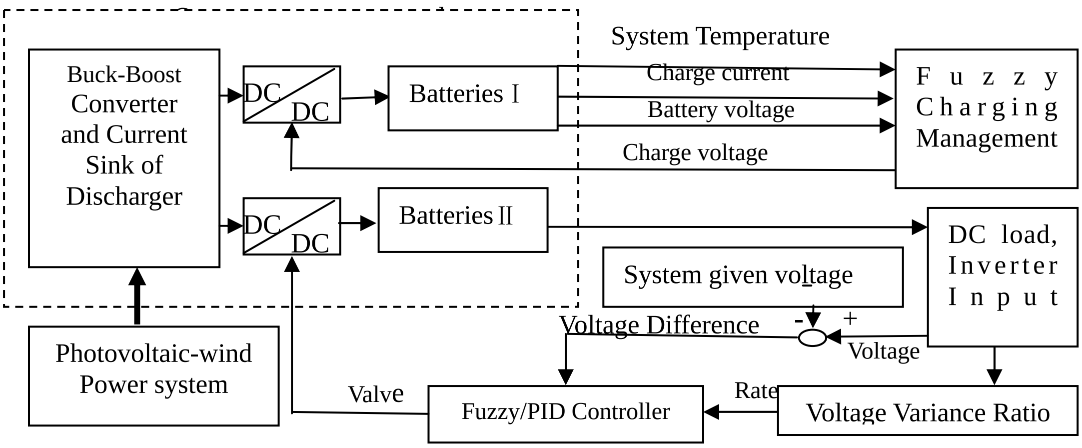

Fig.2 Photovoltaic-wind complementation power system fuzzy control chart

[-0.1, 0.1], and the fuzzy subsets of membership functions are {negative, none, positive}, which choose Gaussian membership functions as follow:

$$u_{negative} = u(x;\delta_n, c_n) = e^{-\frac{(x-c_n)^2}{2\delta_n^2}}$$

here δ_n =0.03 , c_n =-0.1 ;

$$u_{positive} = u(x;\delta_p, c_p) = e^{-\frac{(x-c_p)^2}{2\delta_p^2}}$$

here δ_p =0.03 , c_p =0.1 ;

$$u_{none} = u(x;\delta_o, c_o) = e^{-\frac{(x-c_o)^2}{2\delta_o^2}}$$

here δ_o=0.03， c_o =0.

Output fuzzy variable: the output of fuzzy/PID control is the valve controller (Valve) for voltage and current which adjust the duty ratio of Buck-Boost converter and control the current sink of discharger. For the given storage batteries, the normalization coordinate is [-1, 1], and the fuzzy subsets of membership functions are {decrease-fast, decrease-slow, no-change, increase-slow, increase-fast}, which choose Triangular membership functions as follow:

$$u_{decrease-fast}$$
$$= u(x;a_{df}, b_{df}, c_{df})$$
$$= \max(\min(\frac{x-a_{df}}{b_{df}-a_{df}}, \frac{c_{df}-x}{c_{df}-b_{df}}), 0)$$

Here a_{df} =-1, b_{df} =-0.9, c_{df} =-0.8; So, $u_{decrease-slow}$, here a_{ds} =-0.6, b_{ds} =-0.5, c_{ds} =-0.4; and $u_{no-change}$, here a_{nc} =-0.1, b_{nc} =0, c_{nc} =0.1; and $u_{increase-slow}$, a_{is} =0.4, b_{is} =0.5, c_{is} =0.6; and $u_{increase-fast}$, here a_{if} =0.8, b_{if} =0.9, c_{if} =1;

Fuzzy rules are:

①Rule 1 if (VE is okay) then (valve is no-change)

②Rule 2 if (VE is low) then (valve is increase-fast)

③Rule 3 if (VE is high) then (valve is decrease-fast)

④Rule 4 if (VE is okay) and (rate is positive) then (valve is decrease-slow)

⑤Rule 5 if (VE is okay) and (rate is negative) then (valve is increase-slow)

4 Hardware Frame and Test Result

4.1 Hybrid System Hardware Frame

Photovoltaic-wind complementation energy system is composed of photovoltaic system, wind power system, fuzzy intelligence management, inversion system and energy storage system, et al. See figure 3.

Photovoltaic system and wind power system: Photovoltaic system adopt required power photovoltaic panel to conversion energy of sunlight and manage the charging [5], discharging and inversion of the photovoltaic system through fuzzy intelligence management. Wind power system utilize minitype wind-driven generator to transition wind energy and manage the charging, discharging and inversion of the wind power system through fuzzy intelligence management. Hybrid system has its own feature in collection nature energy. Firstly, the two systems complement each other. Secondly, the photovoltaic system has credible power supply and low operating maintenance cost, while expensive construction cost. On the contrary, the wind power system has high generated energy, low construction cost and low operating maintenance cost, while low system reliability.

Energy storage system: Lead-acid battery is the general energy storage system using in photovoltaic-wind complementation energy system for its low cost, large capacity and maintenance-free characteristic [6]. The reasonable charge-discharge process for storage battery prolong the life of the system for both wind power system and photovoltaic system need lead-acid battery to provide stabilized voltage. The dissertation found a fuzzy charging approach which realize by establishing fuzzy rules

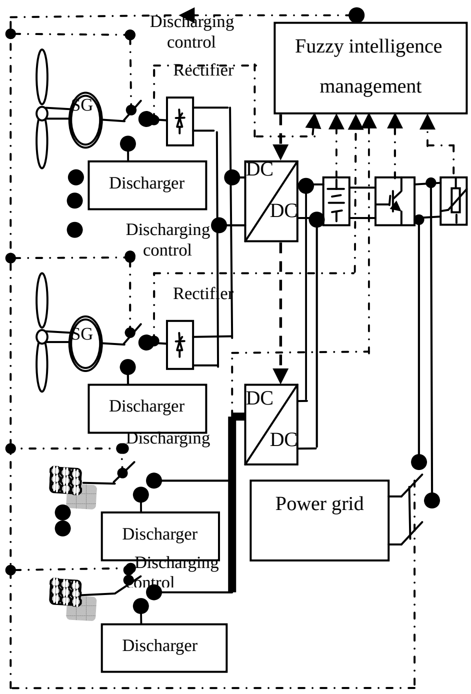

Fig.3 Hybrid wind-solar power system based on fuzzy control

based on expert information on dual-level three states charge. Hybrid photovoltaic-wind power system adopts double stored energy structure which includes two group lead-acid batteries. This configuration make system can charge and discharge at the same time, that means the system can supply the load on the one hand, and on the other hand, when the condition is available for charging, the system will charge the spare battery. The switch between the two group batteries is up to the battery states which are monitored by real time sensors.

DC/DC module：The fuzzy intelligence management drive MOSFETs to turn on or turn off and adjust the duty ratio to make Buck-Boost circuit.

DC/AC module：The system not only provides DC voltage but also can supply AC voltage through inversion module.

Discharger: The excess current sink consists of n parallel banks of three series 1 ohm, 50 watt resistors, so the current sink is capable of dissipating as much as 150*n watts of excess power, which could occur during period of sustained winds exceeding certain meters per second.

Fuzzy intelligence management: This part is the key of the wind-solar system, and is made of LCM (Liquid Crystal Module), keyboard and MCU (micro control unit) etc. It drives the MOSFETs and IGBT to realize the process of DC-DC and DC-AC, at the same time it dispose the system data in real time.

4.2 Hybrid System Test Result

Voltage tracking performance:

After adjusting each module parameter, fuzzy/PID voltage tracking control performance is approximate to PID control only, while is good than fuzzy control only.

Step function responsiveness:

The step response of fuzzy control, PID control and fuzzy/PID control are showed as Fig.4. Fuzzy / PID control not only has simple control structure, strong robustness and high reliability but also wane the overshoot and expedite the response time comparing with traditional PID control. It has a favorable control effect on the hybrid photovoltaic-wind energy system which has delay in time and uncertain in model structure and parameters.

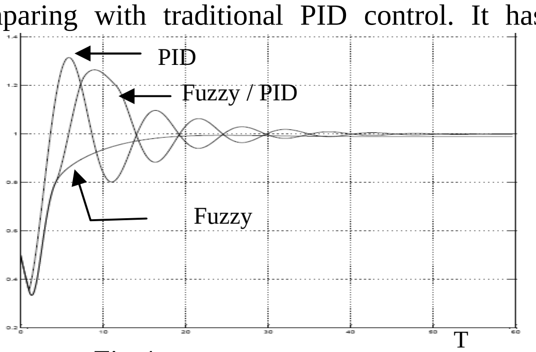

Fig.4 step response compare

5 Conclusion

The photovoltaic-wind power system utilize the natural energy source reasonably on the one hand, and on the other hand, make use of fuzzy technology which has strong adaptability and best robustness, and is good for photovoltaic-wind power system which contains many indetermination quantities and is difficult to describe with precise mathematical model, all these ensure the high efficiency and high reliability of the photovoltaic-wind power system.

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