A Battery Charging Control Strategy for Renewable Energy Generation Systems

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***Abstract*—Battery charging process is non-linear, time-varying with a considerable time delay so it is difficult to achieve the best energy management performance by using traditional control approaches. A fuzzy control strategy for battery charging or discharging used in a renewable power generation system is studied in the paper. Three working status of a battery in different energy transformation modes and the working principles of a re-chargeable battery are studied. To achieve the optimal charging and discharging status of the battery, a fuzzy control strategy is developed. The membership function database of the fuzzy sets, the fuzzification of the input and output variables and the evaluation of the fuzzy rules are studied to support the control strategy. Finally, the output defuzzification and the fuzzy control simulation is presented, which demonstrates that the satisfied system performance is achieved.**

***Index Terms*—Renewable energy generation, battery charging and discharging, fuzzy control.**

I. INTRODUCTION

Under the pressure of limited available energy resources and environmental policies, electrical power generation using renewable energy has rapidly increased in recent years [1]. In China, a large number of remote rural or mountainous inhabitants have no access to the main electricity supply network so it is important to explore the local natural renewable energy resources such as wind or solar [2] for power generation, mainly for local consumptions. Due to the nature of intermittence of renewable energy, the use of the secondary energy storage such as batteries become inevitable which will compensate the fluctuations of power generation [3]. The use of a small size wind turbines could enable more households to have accesses to electricity. A block diagram for the energy conversion process in a small-scale renewable energy generation system is shown in Fig.1.

First, the renewable resource such as wind or tidal energy is used to drive a turbine, translating its power to mechanical form, which then drives a generator. The AC power generated is generally with a variable frequency and unstable voltage so it will be converted to DC power. The DC power either is used to serve the load directly or converted to good quality AC power supply to AC loads. Due to uncertainties of the renewable energy availability, battery storage is adopted. So the electricity energy will be saved to the battery when the excessive electricity is generated and the stored energy will supply electricity to the load while there is no enough electrical power being generated.

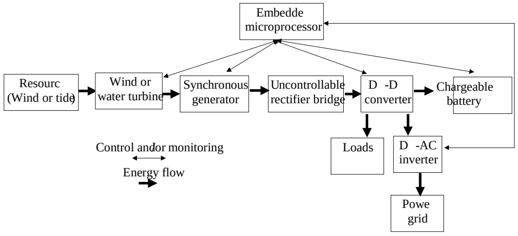

Fig.1 A typical renewable energy generation system

First, the renewable resource such as wind or tidal energy is used to drive a turbine, translating its power to mechanical form, which then drives a generator. The AC power generated is generally with a variable frequency and unstable voltage so it will be converted to DC power. The DC power either is used to serve the load directly or converted to good quality AC power supply to AC loads. Due to uncertainties of the renewable energy availability, battery storage is adopted. So the electricity energy will be saved to the battery when the excessive electricity is generated and the stored energy will supply electricity to the load while there is no enough electrical power being generated.

As we know, frequent charging and discharging will shorten the life time of a battery. With such a system, the problem is how to determine when the battery should be charged to provide the best energy efficiency and to prolong the life time. Many works such as the modelling of the wind turbine, the control strategies for the three-phase generator and the optimization of the DC-DC converter etc., have been reported in many publications [4].This paper focuses on the development of the battery control unit to the system. The energy transformation modes are analyzed, and then the working principles of the chargeable battery are studied. A control strategy based on fuzzy control theory has been proposed to achieve the optimal results of the battery charging and discharging performance.

II. BATTERY WORKING CHARACTERISTICS

The energy transformation modes in the renewable energy generation system can be demonstrated in Fig.2.

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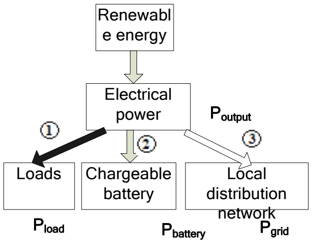

Fig.2. Energy transformation mode

In the system, the output electrical power is provided to the loads with the highest priority. If the output electrical power is excessive for the demands of the loads, the surplus is used to charge the battery. Provided that the loads can't use up the whole output power, and the battery is fully charged, the superfluous power is then sent to the local distribution network if it exists. The battery works in three statuses: disconnected from the system, charged by the system or discharged to supply power to the loads, as shown in Fig.3. The status of the battery is dependent on the working modes of the system, and shifts according to different modes [5].

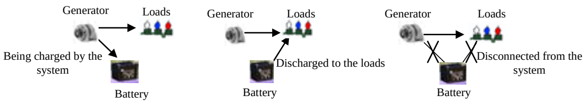

Fig.3 Three working status of the battery

In the 20th century, America scientist Mass [5] has put forward the optimal charging curve of the Lead-acid battery based on the lowest output gas rate, as shown in Fig.4. If the charging current keeps to the track of the optimal curve, the charging hours can be sharply cut down without any side effect on the capacity and life-span of the battery. It is designated that the charging current expressed in amperes at any moment of the charging cycle must not overpass the capacity of the battery at that moment, expressed in Ampere-hours. Formula (1) expresses the relationship between the charging current and charging time [6].

$$i = I_0 e^{-\alpha t} \tag{1}$$

In formula (1), the variable i is the value of the instant charging current in each moment. I_0 is the initial charging current value, namely when $t = 0$, $i = I_0$. I_0 expresses its current adoption capacity. It is apparent that I_0 is the maximum charging current value in the whole process. The constant α represents the attenuation coefficient of the battery.

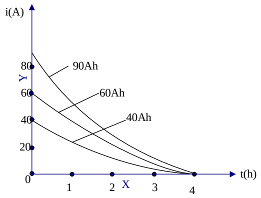

Fig.4. Optimal charging curve of the battery

The Ampere-hour rule for charging the Lead-acid batteries can be considered as the most efficient charging approach, considering the charging time and the excellent performance provided by this method to maintain the life-span of the battery. One example of the application of the Ampere-hour rule to charge battery is shown in Fig.5. More details in charging method for lead-acid batteries was discussed in reference [7, 8]. In here we only discuss the charging task with two phases.

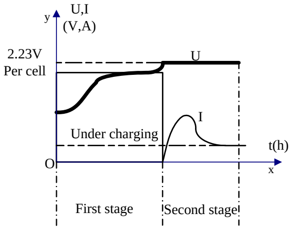

Fig.5. Application of the Ampere-hour rule to charge battery

When the battery is charged, the charging current I_c, the charging voltage (port voltage) U_c, the potential difference E_b between the positive plate and the negative plate of the battery and the internal resistor R_b of the battery has the following relationship:

$$I_c = \frac{U_c - E_b}{R_b} \tag{2}$$

As can be seen from the formula (2), only on conditions that $U_c > E_b$, the battery can be charged. The potential difference E_b between the plates changes with the charging process.

During the first stage, the E_b is very low, so the port voltage U_c starts with a small value, while the current keeps constant to the set value, namely the maximum current value. The set point of the charging current is closely related with the capacity of the battery [9]. With the potential difference of the battery gradually increasing, the charging voltage rises with it so that the battery can be charged according to the formula (2), but it kept below a certain maximum level which is also defined according to the characteristics of the battery, as shown in the part one of Fig.5.The second stage starts when the battery voltage reaches a certain level, which is defined by the characteristics of the battery, depending again on the capacity and number of cells available in the battery. Generally this is taken as 90% of the total capacity of the battery. During this phase, the control variable switches over from current to voltage. The voltage is maintained almost unchanged at a given value, while the current is gradually decreasing until it drops to a value set at the initial stage [10].

As we can see from the above discussion, the charging process of the battery is much complex. It is quite different to obtain the benefit of the reduction in charging time, the high efficiency of the energy transformation and the maintenance of the life span of the battery. Moreover, the control system of the battery charging and discharging process is a non-linear, time-varying system with pure time delay, multiple variables and many outer disturbances. In its charging and discharging process, many parameters such as the charging rate, the permitted maximum charging current, the internal resistor, the port voltage, the temperature and moisture, the life-span etc. vary with different battery. Some parameters change during the charging and discharging process and can't be obtained directly. Furthermore, as these parameters are coupling with each other, sometimes it is impossible to use traditional control system. Under this circumstance, a fuzzy control system is adopted to control a the battery charging and discharging process that cannot be controlled well by a conventional control system, such as PID, PD, PI etc, and it will be discussed in detail in the next section.

III. CHARGING AND DISCHARGING CONTROL STRATEGIES

In general, to charge and discharge the battery frequently will shorten its life time, and it also should be avoided to overcharge or insufficiently charge the battery. The wind speed is always unstable naturally. With such a renewable energy generation system, the problem is when and how the battery should be charged to provide the best energy efficiency and to prolong the life time.

If the output electrical power is excessive for the consumption of the loads, the surplus is provided to charge the battery. As shown in Fig.6, from the period t1 to t2 and t7 to t8, the wind power is more enough than that of the load consumption, and it lasts long, so the battery may be charged, while from t3 to t4 or t5 to t6, even though the load can't use up the wind power, it should prohibit the battery from being charging insufficiently or too frequently.

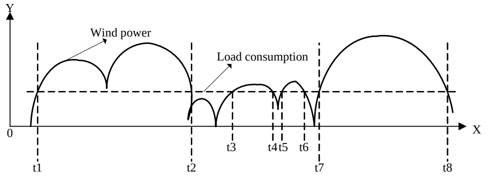

Fig.6. Relatinship between the wind power and the load consumption

It is extremely difficult to determine whether the battery should be charged or to prevent it from being over or insufficiently charged based on certain traditional mathematical model, so systems based on empirical rules may be more effective. We employ fuzzy control strategy to solve this problem that will be discussed in detail in the following sections.

A. Fuzzy control introductions

To achieve the optimal charging and discharging performance suggested in Section 2, a fuzzy control algorithm is developed in this section.

Fuzzy logic - a mathematical system analyzes analogue input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 0 and 1 (true and false). Fuzzy logic is widely used in the control field. It has the benefit that some problems can be expressed in terms that human can understand, so that human expert experience can be used in the design of the controller [11].

Traditional controls are the results of decades of development and theoretical advances, and they are quite effective in some fields [12]. However systems based on Fuzzy control algorithm have some advantages over the traditional control methods. In many cases, the mathematical model of the control process may not exist, so systems based on empirical rules may be more effective. Also, fuzzy logic can be well implemented to low-cost systems based on cheap sensors, low-resolution analogue-to-digital converters, and 4-bit or 8-bit microcontrollers. Such systems can be easily updated by amending new rules to improve performance or adding new features. For more details in Fuzzy logic, see [11] and [12].

B. Membership function database

Referred to the Ampere-hour charging curve of the battery in Fig.5, the charging process seems infinite. At the very beginning, the charging current is quite large, while it drops quickly with time elapses. During this period, most electrical power has been converted into chemical energy. At the end of the charging process, the current is close to zero and hardly changes. In general when the charging capacity of the battery reaches 90% of its Rating one, the charging process is considered to complete.

In this system, there are four input variables, as shown in formula (3).

$$\Delta P = P - P_n,\ \Delta P' = \frac{d\Delta P}{dt}$$

$$\Delta T = T_n - T,\ \Delta T' = \frac{d\Delta T}{dt} \qquad (3)$$

In formula (3), ΔP is the difference of the wind power P minusing the load consumption P_n; $\Delta P'$ represents the changing rate of ΔP; ΔT expresses the relative temperature of the battery to the normal indoor one; $\Delta T'$ gives the changing rate of ΔT. The output variable is the charging voltage U. Therefore, the control function can be described as formula (4).

$$U=F\ (\Delta P, \Delta P', \Delta T, \Delta T') \qquad (4)$$

The general fuzzy rules can be represented as formula (5).

If (ΔP is … and $\Delta P'$ is … and ΔT is… and $\Delta T'$ is…)
Then (U is …) (5)

Fig.7 shows the block diagram of the fuzzy rules in formula (5).

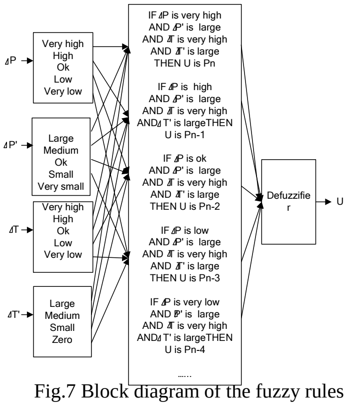

Fig.7 Block diagram of the fuzzy rules

In this paper, an improvement on the organization of the fuzzy rules has been considered to simple the system. According the control function in formula (5), the fuzzy rules can be organized with two separate parts, as shown in formula (6) and (7).

$$U1=F1\ (\Delta P, P') \qquad (6)$$

$$U2=F2\ (\Delta T, \Delta T') \qquad (7)$$

The fuzzy rules for them can be described in formula (8), (9) and (10).

If (ΔP is … and $\Delta P'$ is …) then ($U1$ is …) (8)
If (ΔT is… and $\Delta T'$ is…) then ($U2$ is …) (9)

$$U1 \otimes U2 = U \qquad (10)$$

The improved fuzzy rules can be demonstrated with the block diagram in Fig.8.

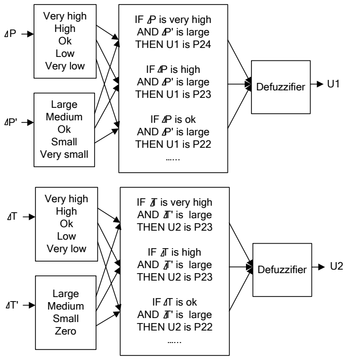

Fig.8 Block diagram of the fuzzy rules

The improved strategy is much simpler, which can be implemented with two control loops. The outer loop is based on the ΔP and $\Delta P'$, while the inner loop is on the basis of the ΔT and $\Delta T'$. The controller according to the above fuzzy rules can be implemented as Fig.9.

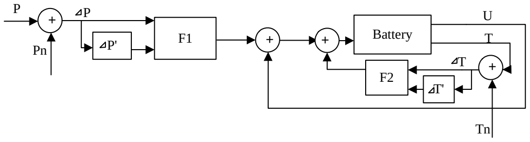

Fig.9 Fuzzy control based on improved rules

In Fig.9, *F1* and *F2* are the control functions realized with the fuzzy algorithm, according to formulae (6) and (7) individually.

C. Fuzzification

The fuzzification of the system has two separate parts. One is for the outer loop and the other is for the inner loop. As the fuzzification of the outer control loop is much the same as that of the inner loop, we only present the discussion of the outer loop in the paper.

The input variables for the outer loop is the ΔP and $\Delta P'$. ΔP is positive in the whole charging process. At the same time, it drops gradually in the whole process. As $\Delta P'$ is the differential coefficient of ΔP to t, it can be positive or negative in the charging process. In this case, we label ΔP with the following values, given a value set of X in [0, +1]:

PV: Positive very high
PH: Positive high
PO: Positive ok
PL: Positive low
PZ: Positive but close to zero

While $\Delta P'$ is labeled with the following values, defined a value set of X in [-1, +1].

PL: Positive large
PM: Positive medium
PZ: Positive but close to zero
NM: Negative medium
NL: Negative large

The fuzzification of ΔP and $\Delta P'$ is shown in Fig.10.

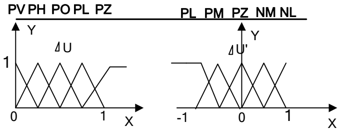

Fig.10 Input variables fuzzification

As the output variable *U1* can be positive or negative, we label it with five possibilities as follows:

LP: large positive
SP: small positive
ZE: zero
SN: small negative
LN: large negative

The fuzzication of the output *U1* can be demonstrated in Fig.11.

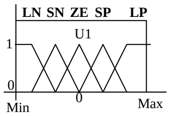

Fig.11 Output variable fuzzification

Another approach is to label them with the minimum and maximum values of the analogue to digital converter, such as the set of [0, 255] or [-255, 0] with an 8-bit converter. For more details, please see the reference [13].

D. Fuzzy rule evaluation

Fuzzy rule evaluation is the key step for a fuzzy logic control system. This step processes a list of rules from the knowledge base using input values (commonly a table of constants) from RAM to produce a list of fuzzy outputs to RAM. From the beginning of the application of the fuzzy theory till now, there are many experienced methods to evaluate the fuzzy rules, among which State space method is the most popular one due to its close relation with the transference function of the system [13]. The rule base for outer loop in this system is shown in Table.1.

Table.1 rule base for outer loop

ΔP' \ ΔP	PV	PH	PO	PL	PZ
PL	P24	P23	P22	P21	P20
PM	P19	P18	P17	P16	P15
PZ	P14	P13	P12	P11	P10
NM	P9	P8	P7	P6	P5
NL	P4	P3	P2	P1	P0

We have to study the fuzzy rules again here. Fuzzy rules involves controlling rules that relate the input variables to the output model properties. These rules are expressed in the form of IF - THEN, as generally given in formula (5). In here, we specify the fuzzy as the form in formula (11).

rule 1: IF $\Delta P = PV$ *AND* $\Delta P' = NL$ *THEN* $U1 = ZE$
rule 2: IF $\Delta P = PV$ *AND* $\Delta P' = NM$ *THEN* $U1 = SN$
rule 3: IF $\Delta P = PL$ *AND* $\Delta P' = PZ$ *THEN* $U1 = LP$
rule 4: IF $\Delta P = PV$ *OR* $\Delta P' = PM$ *THEN* $U1 = LN$
……
rule n: IF $\Delta P = \ldots$ *OR/AND* $\Delta P' = \ldots$ *THEN* $U1 = \ldots$ (11)

To work out the values of the output *P0* to *P24* in Table.1, the Min - Max method was selected in the rule evaluation process [13]. In the Min - Max rule, the minimum of the two inputs is used as the combined truth-value. Fig.12 displays this method.

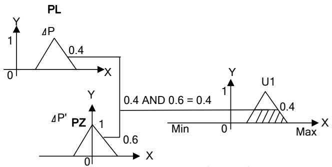

Fig.12 Output variable fuzzification

Combining with rule3, we can solve out that *P11* equals 0.4 but belongs to LP.

E. Defuzzification and Simulation

The final step in the fuzzy logic controller is to defuzzify the output, combining the fuzzy output into a final systems output. There are a lot of methods to defuzzify the fuzzy output in theory, each with various advantages and disadvantages. The Centroid method is very popular, which favours the rule with the output of greatest area [14][15].

Considering formula (11), there are lots of fuzzy rules defined in the system, but we only consider the first four rules. The rule outputs can be defuzzified using a discrete centroid computation described in formula (12).

$$U_{out} = \frac{\sum_{1}^{4} Si * Fi}{\sum_{1}^{4} Si} = SUM\,(\,i = 1 \text{ to } 4 \text{ of} (\,S(i) * F(i)\,)\,)\,/\,SUM\,(\,i = 1 \text{ to } 4 \text{ of } S(i)\,) = \frac{S(1) * F(1) + S(2) * F(2) + S(3) * F(3) + S(4) * F(4)}{S(1) + S(2) + S(3) + S(4)} \tag{12}$$

In formula (12), *S (i)* is the truth value of the result membership function for rule *i*, and *F (i)* represents Value (for rule *i*) while the result membership function (ZE) is maximum over the output variable fuzzy set range.

With knowledge discussed above, we use Matlab7.0 to simulate the fuzzy control system of the battery charging process, and the monitored output port voltage and charging current are given in Fig.13.

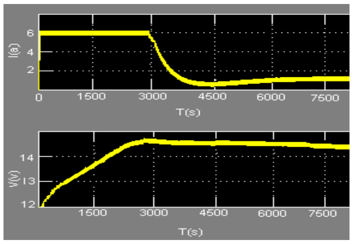

Fig.13 Output variable fuzzification

In the simulation, we set the point of the charging voltage to 14.5V and that of the charging current to 6A. We separate the charging process into two stages. During the first stage, the fuzzy control strategy is implemented to determine the proper start charging time and to prevent it from being over or insufficiently charged. At the beginning, the port voltage U_c starts with a small value, while the current keeps constant to the set value, so the battery will be fully charged. During the second stage, we utilize the normal charging method. The control variable switches over from current to voltage. The voltage is maintained almost unchanged at a given value, while the current is gradually decreasing until it drops to a value set at the initial stage. As can be seen from Fig.13, the performance of the fuzzy controller proves to be very good, and the charging curve is much close to the Ampere-hour curve in Fig.4. Charging time in this method has been reduced to about 30%, comparing to the classical methods. For a fully discharged battery, the required charging time is approximately 2.5 hours (9000 seconds). The efficiency of the energy saved by method is one of the encouraging reasons to implement the method in industrial environments.

IV. CONCLUSION

The control process of the battery charging and discharging is non-linear, time-varying with time delays. It is a multiple variable control problem with unexpected external disturbances. Many parameters such as the charging rate, the permitted maximum charging current, the internal resistor, the port voltage, the temperature and moisture, *etc.* keep changing during the charging and discharging process and can’t be directly obtained, so it is difficult to achieve the optimal operation performance by using traditional control methods. A fuzzy control unit for battery charging and discharging used in a renewable energy generation system is studied in details. Simulation results based on fuzzy strategies show that the control unit has satisfied performance in a laboratory environment. Analysis involved in the paper ignores the temperature element in the inner loop of the control unit, but to utilize this unit in a real environment, changes in the temperature must be taken into account.

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