Research on energy management of vehicle-mounted PV/energy storage dc micro-grid

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Abstract. The application of multi-energy systems in urban rail vehicles have attracted increasing attention. However, the existing studies were mainly focused on high-voltage systems, but rarely on low-voltage multi-energy systems. Based on the world's first hybrid fuel cell/supercapacitor 100%-low-floor tram, a model of vehicle-mounted PV/energy storage low-voltage DC micro-grid is proposed for the train’s 24V DC loads. Moreover, an energy management strategy based on Fuzzy control is proposed to achieve the sufficient consumption of PV power and the reasonable SOC distribution of the battery. The calculation results show that the proposed low-voltage multi-energy system can meet the load demand and the battery constraints, and the PV utilization rate is as high as 99.8%.

1. Introduction

More and more attention has been paid to multi-energy systems [1] in the transportation field. Among them, hybrid hydrogen fuel cells especially have been widely used. Recently, the authors’ team developed the world’s first hybrid hydrogen fuel cell 100% low-floor tram [2]. However, at present, the price of hydrogen is relatively high in China with usually above 60 ¥/kg, and the fuel cell power generation cost is already 4 ¥/kWh. At the same time, the auxiliary power systems of trams often adopt 24V bus, and require buck conversion with an energy efficiency reduction. Therefore, a vehicle-mounted 24V DC microgrid is developed with the connected PV/energy storage system and the original 24V power supply unit, which not only extends the mileage of vehicles, but also promotes the energy efficiency and operational economy.

The access to photovoltaic power generation system changes the original energy structure of the power supply system of the tram. In order to improve the energy efficiency of the system and enhance the PV energy absorption, a corresponding DC microgrid energy management strategy needs to be developed. It should be noted that the existing studies were not conducted on vehicle-mounted microgrid of multi-energy systems, but on ground-mounted PV and other energies, taking a community for example [3]. The existing studies on energy management strategies for the vehicle-mounted multi-energy systems include drop control, V-f control, PQ decoupling control, etc. [2], but these strategies do not take into account the volatility and randomness of PV output, and when the PV output power is higher than the load, the PV system will operate with reduced power due to excess power, resulting in energy waste and reducing system economics.

In order to suppress the phenomenon of light abandonment, national and international experts and scholars introduce modern intelligent algorithms, such as particle swarm algorithm, neural network
method, fuzzy logic control and other modern intelligent algorithms into the microgrid energy management [4-6]. Among them, the fuzzy logic control has the characteristics of strong robustness and high fault tolerance, does not rely on an accurate mathematical model and is easy to implement, which is one of the hotspots in recent years in the study of micro-grid energy distribution management strategies [7]. Therefore, based on the world's first hybrid fuel cell-supercapacitor power 100% low floor tram as a prototype car, an energy management based on fuzzy control is proposed for the vehicle-mounted 24V DC micro-grid for urban rail transit.

The rest of the paper is organized as follows. In Section 2, the vehicle-mounted DC micro-grid system is introduced. Section 3 will calculate the vehicle-mounted PV power generation capacity. Then, the system model and energy management strategy are described in Section 4 and 5, respectively. Moreover, simulation results and conclusion are presented in Section 6 and 7, respectively.

2. Vehicle-mounted DC micro-grid system

Based on the roof space of the world's first hybrid fuel cell tram, the installed PV capacity is 2.675 kWp. The vehicle-mounted PV, original power source from 750V bus and energy storage battery jointly supply electric power for the auxiliary system of the tram, constituting the on-board 24V DC micro-grid system, as shown in Figure 1. In the process of energy management, maximum power point tracking (MPPT) of PV system is a very important and some important progress has been made in the existing researches [8, 9]. Considering the mobility of the vehicle-mounted photovoltaic system, the MPPT algorithm proposed by the author in Ref. [10] is adopted.

Figure 1. 24V DC microgrid system of trams.

3. Calculation of vehicle-mounted PV power generation capacity

The area where PV modules can be installed in the tram mainly consists of the roof and the two sides of the tram. For the world's first hybrid fuel cell 100% low floor tram, the fuel cell and energy storage units are arranged on the roof of the tram. So, the locations where solar panels can be installed on the roof include fuel cell cabinet, unidirectional DC/DC cabinet, energy storage cabinet, bidirectional DC/DC cabinet, and hydrogen storage system cabinet. The side walls are mainly installed on the train apron and slope area, which has an angle of 78° relative to the ground.

In combination with the actual tram and the dimensions of the installed area of the PV modules, the installed capacity and power generation of the PV power generation system of the rail locomotive is calculated. The standard module of CIGS, HN-233, is selected.

According to the installed capacity of the photovoltaic power generation system and the parameters of photovoltaic modules, the installable PV capacity is calculated as shown in Table 1. From the Table 1, the power generation efficiency of roof-mounted PV modules is much higher than others, so PV modules are installed only on the tram roof. The total capacity of CIGS is 2675Wp.
Table 1. The daily power generation of vehicle-mounted PV systems.

| Installed capacity/Wp | 5,960 | 2,559 |
|-----------------------|-------|-------|
| Inclination angle/*   | 78°   | 0°    |
| Orientation           | east  | south | west  | north | upper |
| Daily average generated energy/Wh | 9,188 | 12,481 | 9,188 | 3,987 | 6,370 |
| Generation efficiency/% | 35.3  | 47.9  | 42.3  | 35.3  | 57.0  |

4. System model

4.1. PV model

The output power of PV modules is calculated based on the ground temperature and solar light intensity in Tangshan, where the tram is located. The temperature and light intensity data were obtained from the China Meteorological Data Network. The installed capacity of CIGS solar cells installed on the roof of the train is 2675 Wp, based on the historical environmental parameters (light intensity, ambient temperature) of Tangshan and other data according to the formula (1 to 4) to establish a photovoltaic power generation system output model, the whole year and 48 hours of photovoltaic output results shown in Figure 2 and Figure 3.

\[
I_{mn} = I_{mp} \left( \frac{S_i}{S_b} \right) (1 + a\Delta T) \tag{1}
\]

\[
U_{mn} = U_{mp} (1 - c\Delta T) \ln(e + b \frac{S_i}{S_b}) \tag{2}
\]

\[
P_{PV} = f \cdot K \cdot I_{mn} \cdot U_{mn} \tag{3}
\]

\[
\Delta T = T_i - T_b \tag{4}
\]

where, \(I_{mp}\) - the peak power current in the standard test environment of the PV system;

\(I_{mn}\) - the peak power current in the current environment;

\(U_{mp}\) - the peak power voltage in a standard test environment for photovoltaic system;

\(U_{mn}\) - the peak power voltage in the current environment.
4.2. Load model
The main load type and power are shown in Table 2. From Eq. 5, a probabilistic load model is established, with a minimum total load power of 6 kW and a maximum of 21 kW, the daily load model is shown in Figure 4 and a 48 hours’ load model is shown in Figure 5.

| Load                                | Quantity | Power /W | Load rate/% | Actual power/W |
|-------------------------------------|----------|----------|-------------|----------------|
| Lighting electricity                | 154      | 2        | 51.7        | 154            |
| vehicle-mounted controller          | 1        | 60       | 100         | 60             |
| smoke detector                      | 2        | 10       | 100         | 20             |
| Electromagnetic track brake         | 2        | 643.2    | 5           | 64.32          |
| Electric whistle                    | 1        | 70       | 25          | 17.5           |
| Remote commutator                   | 2        | 4400     | 68          | 2992           |

\[
P_t = \sum \text{floor}\left(\text{rand}\left(0,1\right)/\alpha_i\right) \cdot P_i \cdot N_i
\]  
where: \( \text{floor}(\cdot) \) - down integral function.

From Figure 5, we can see that the train departs at 7:30, 10:30, 13:30 and 16:30, and runs for 50 minutes.

4.3. Energy storage model
There are two types of conventional batteries which are lead-acid and lithium-ion batteries, and their service life is affected by the depth of charge and discharge. Ref. [11] showed the corresponding relationship between the discharge depth and cycle life of lead-acid batteries, and Ref. [12] showed the corresponding relationship between the discharge depth and cycle life of lithium-ion batteries.

On this basis, the cost of charging and discharging of the two batteries under different discharge depths in the full life cycle is calculated with the price of lithium-ion batteries at 2 RMB/W and lead-acid batteries at 1 RMB/W, and the results are shown in Figure 6.

From Figure 6, lithium-ion battery has much higher cycle times and lower costs with the same discharge depth. Therefore, lithium-ion battery is chosen for this study. According to the simulation results, the optimal discharge depth of lithium-ion battery is 0.6, thus setting the ideal SOC range of the battery from 0.2 to 0.8.

5. Energy management strategy based on fuzzy logic
In the vehicle-mounted microgrid, photovoltaic directly supplies electric power for low-voltage loads. When the photovoltaic energy cannot be absorbed by the loads, photovoltaic can charge the energy...
storage battery; when the SOC of energy storage battery is high (such as SOC > 0.6), it can also supply electric power to the loads; when the photovoltaic and energy storage cannot meet the load demands, the power source from 750 V bus is used to supply electric power to the loads.

The fuzzy process consists of three basic steps: (1) fuzzification: the process of obtaining the affiliation of fuzzy sets from specific inputs according to the affiliation function; (2) reasoning method: the method of obtaining fuzzy conclusions from the affiliation of fuzzy rules and inputs to relevant fuzzy sets; (3) defuzzification: the process of converting fuzzy conclusions into concrete and accurate outputs. In this paper, the SOC and PV power output of the battery are used as fuzzy input variables and battery output power as output variables to establish a fuzzy logic control strategy, the control strategy are shown in Figure 7.

5.1. Fuzzification for PV output
According to the actual maximum PV output power in Tangshan, the PV installation capacity is 2500W, the output range of PV module is set from 0 to 3000 W. The fuzzy control section is divided into five power ranges-LL (very low), LM (low), MM (medium), MH (high), HH (very high). A trapezoidal affiliation function is selected with the input range divisions: [0 0 200 500], [200 500 700 1000], [700 1000 1200 1500], [1200 1500 1700 2000], and [1700 2000 3000 3000].

5.2. Fuzzification for the SOC of the battery
The cell SOC control range is 0.2~0.8, which can be dynamically adjusted to 0.2~1 when the PV module output power is high. Means that the cell is allowed to be in a floating charge state when the PV module output power is too high, and the SOC states are divided into ZZ (full discharge), ZL (very low), LL (low), LM (medium-low), MM (medium), MH (medium-high), HH (high), and HF (full charge). Its affiliation function input range is divided into [0 0.2 0.3], [0.2 0.3 0.4 0.5], [0.4 0.5 0.6], [0.5 0.6 0.7], [0.6 0.7 0.8], [0.7 0.8 0.9], [0.8 0.9 1], [0.9 1 1.05] with a trapezoidal and triangular mixed affiliation function.

5.3. Fuzzification for battery output power
The battery installation capacity is 120Ah * 24V * 2 groups. In order to extend the battery life, the maximum charge and discharge rate is 1C, which means the power is -5760 ~ 5760 W. Therefore, the fuzzy logic state is divided into NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PL (positive large). Its affiliation function input ranges are [-5760 -5760 -4500 -4000], [-4500 -4000 -2000 -1800], [-2000 -1800 -1000 -500], [-1000 -500 500 1000], [500 1000 1800 2000], [1800 2000 4000 4500], [4000 4500 5760 5760] with a trapezoidal and triangular mixed affiliation function. Based on the fuzzing variables described above, a table of energy management strategy rules is created as shown in Table 3.

**Table 3. Table of fuzzy control rules.**

| SOCP | ZZ | ZL | LL | LM | MM | MH | HH | HH |
|------|--|----|----|----|----|----|----|----|
| LL   | NL | NL | NL | NL | NL | NL | NL | NL |
| ZL   | NL | NL | NL | NL | NM | NM | NS | NS |
| LL   | NL | NL | NM | NS | ZE | ZE | ZE | ZE |
| LM   | NL | NM | NS | ZE | ZE | PS | PS | PS |
| MM   | NM | NS | ZE | ZE | PS | PM | PM | PM |
| MH   | NS | ZE | ZE | PS | PM | PM | PM | PM |
| HH   | ZE | ZE | PS | PM | PM | PL | PL | PL |

6. Results and discussion
Simulation are performed based on the described 24V DC micro-grid system of the tram, combining the model in Section 4 and the fuzzy energy management strategy in Section 5. Figure 8 shows the
variation of PV module power output and SOC of the energy storage with load for the micro-grid under ambient parameter conditions on April 6, 2018.

From Figure 8, it can be seen that before 6:00, there is no solar light and the tram is no operation, and, at this time, the SOC of the energy storage remains unchanged. After that, the PV generation system starts to work while the tram is still no operation. Then, the energy generated by the PV is absorbed by the energy storage system and the SOC slowly rises. At 7:30, the tram starts to work, but the solar light conditions are poor in this time, in order to protect the train still runs safely for 10 minutes after the main power supply is disconnected, the PV generation system and the original power supply system are both the energy storage system, and the SOC value continues to rise to 0.77.

At 8:30, the tram stopped running and the main power supply was disconnected, the load power was provided by PV and energy storage system, the battery SOC fell off rapidly, and the load stopped working at 8:40 when SOC becomes 0.43, and the PV power generation system charged the energy storage. At 10:30, the tram worked again, and the SOC value of energy storage was 0.78. At this time, the output power of the PV system is increased due to the increase of solar light intensity. In order to ensure that the energy storage is able to absorb the energy generated by the PV during the next intermittent period, the energy storage system actively supplies energy to the load while the tram is under operation. The value of SOC is controlled at about 0.71 before the main power supply is disconnected (11:30), and rises to 0.84 before the next tram operation, briefly breaking through the SOC limit range and quickly dropping back down. It repeats the above process until the locomotive stops running at 17:40. Under the control described in this paper, the SOC of the energy storage was always above the limit range of 0.2 on April 6, and all the energy generated by the PV was absorbed.

However, when the PV output power is too large, the energy storage system may still be in a floating charge state, as shown in Figure 9. During the second operation period, when the PV output power was high, and changed the energy storage SOC value to 0.64, this system absorbed the energy generated by the PV during the tram shutdown. However, the PV output power is reduced briefly and then increased rapidly. So that before the third operation, the SOC value of energy storage is equal to 1, and the energy storage is already at the floating charge state, and the PV power generation system operates with reduced power, so that part of the solar energy is not converted into electrical energy.

7. Conclusions
Considering the green development of urban rail transit vehicles and the influence of 24V bus power taking from 750V bus on energy efficiency, a scheme of vehicle-mounted photovoltaic / energy storage DC micro-grid was proposed, and the energy management strategy of micro-grid based on fuzzy control was studied.

Using the world's hybrid first fuel cell 100% low-floor tram as the prototype vehicle, simulation analysis based on 2018 annual data showed that the 24V DC micro-grid system of the tram proposed in this paper could not only meet the 24V load power demand with zero load loss throughout the year, but also the PV annual energy utilization rate is as high as 99.8%. The charge/discharge ratio of the
energy storage system is always within 1C, the SOC is above the lower limit (0.2) and there is no overcharge. Of course, this study still needs to be verified by actual experiments and economic feasibility analysis. This will be the next step of the authors’ work.

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