Energy Management of Hybrid Storage in Distributed Generation System

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Abstract: This paper focuses on energy management of hybrid storage system which consists of batteries and flywheel in distributed renewable generation system including a wind turbine, photovoltaic panels, batteries and a flywheel system. According to states of charge (SOC) of the battery array and the flywheel system, there are several modes in storage system. Control strategy for each mode is described in both grid-connected and islanded operations, based on the characteristics of battery-array (as a long-time storage) and flywheel system (as a fast-dynamic storage). With the control strategies, power can be kept balanced in distributed renewable generation system to reduce fluctuation of wind and solar to utility grid work in islanded operation. Simulation results are shown to verify the control strategies.

Keywords: battery, flywheel, distributed renewable energy generation, energy management

1. INTRODUCTION

With the rapid development of wind power and solar power, an energy storage system is essential in a distributed renewable energy generation system not only for the power supply capacity in islanded operation, but also for reducing the fluctuation of wind and solar to utility grid. An energy storage system with all the features of high energy density, fast response, low cost and long lifetime is desired. However, the energy storage system based on single storage medium can only have parts of the above features. Battery-based system has a big energy capacity, low cost and easy maintenance but slow response[1]. Super-capacitor has a fast response but small capacity and high cost. Therefore, a hybrid storage system combined by both batteries and super-capacitors, with an energy management system and power converters, has been studied and applied widely in distributed renewable energy generation systems[2, 3].

Another option of hybrid storage system is constructed by battery and flywheel, illustrated as Fig.1, where a battery-array is used to provide a long-time stable islanded operation and a flywheel system is used to provide the fast response to the power requirement. Comparing to the super-capacitor, a flywheel system has a longer lifetime, lower cost in full life cycle and more environmentally friendly features.

This paper proposes a novel energy management strategy for the battery-flywheel hybrid storage system, illustrated as Fig.1, in both grid-connected and islanded operations based on characteristics of battery-array and flywheel system.

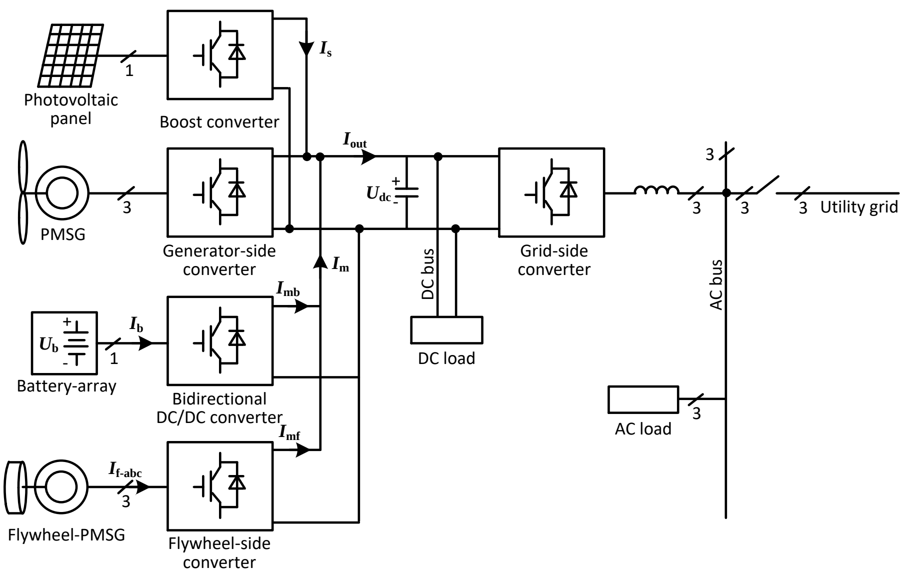

Fig. 1 Distributed generation system with hybrid DC and AC bus

2. WORKING MODES OF HYBRID STORAGE SYSTEM

SOCs of the battery-array and flywheel system are the essential factors for the energy management of the whole hybrid energy storage system. The SOC of the flywheel system is proportional to its speed, which can be calculated easily. But it's not every easy to estimate the SOC of the battery-array for there is no definite functional relation between the terminal voltage and SOC. The SOC of the batter-array is estimated by the online calculation method based on the Kalman filter and system parameter integration detailed in [4].

According to the characteristics of the flywheel system and the battery-array, the working state of the flywheel system is assigned as normal state when its SOC is between 20% and 90%, low state when its SOC is lower than 20% and high state when its SOC is higher than 90%, and the working state of the battery-array is assigned as normal state when its SOC is between 30% and 90%, low state when its SOC is lower than 30% and high state when its SOC is higher than 90%. Therefore, the working states of the hybrid storage system can be listed as Table 1. In practical system, the control strategy will be shifted according to the different working modes in Table 1 and different grid conditions of the utility grid. For the convenience of description, the 9 working states in Table 1 can be classified into 4 groups as following[5]:

- The battery-array and the flywheel system are both in normal mode: Model M_{NN}.
- The battery-array is in normal mode but the flywheel system is in abnormal mode: Mode M_{LN} and Mode M_{HN}.
- The battery-array is in abnormal mode but the flywheel system is in normal mode: Mode M_{NL} and Mode M_{NH}.
- The battery-array and flywheel system are both in abnormal mode: N_{LH}, M_{HL}, M_{LL} and M_{HH}.

This paper will focus on the control strategy of the hybrid energy storage system in both of grid-connected and islanded operations in different working modes.

Table. 1 Modes based on SOC of storage system
SOC_f – SOC of the flywheel system
SOC_b – SOC of the battery-array

SOC_b / SOC_f	low <30%	normal 30% – 90%	High >90%
low <20%	M_{LL}	M_{LN}	M_{LH}
normal 20% – 90%	M_{NL}	M_{NN}	M_{NH}
high >90%	M_{HL}	M_{HN}	M_{HH}

3. CONTROL STRATEGIES IN DIFFERENT MODES

To keep the power balance inside the distributed generation system and reduce the effect of the power fluctuation to the utility grid, the energy storage system will be used to absorb or release the power difference between the power outputted by the renewable generation units and the power consumed by the loads, which can be described by (1) when the converter loss is ignored.

$$P_s = P_b + P_f = P_{wind} + P_{solar} - P_{load} \quad (1)$$

Where P_s indicates the total power absorbed by the storage system, P_b indicates the power absorbed by the battery-array, P_f indicates the power absorbed by the flywheel system, P_{wind} indicates the power outputted by the wind turbine generator, P_{solar} indicates the power outputted by the photovoltaic panel and P_{load} indicates the power absorbed by the loads.

It can be known from (1) that the total power absorbed by the storage system P_s can be calculated by measuring the power outputted by the wind turbine generator and the photovoltaic panel and the power absorbed by the loads, which indicates the P_b and P_f should be assigned according to the characteristics and SOCs of the battery-array and the flywheel system.

The bidirectional DC/DC converter for the battery-array in Fig.1 is under the constant current control illustrated as Fig.2, where the power absorbed by the battery-array can be controlled by regulating the current of the battery-array. The flywheel-side converter in Fig.1 is under the typical vector control, where the power absorbed by the flywheel system can be controlled by regulating the torque current of the flywheel-PMSG. By measuring the terminal voltage and the speed, the charging current of the battery-array and the flywheel system can be obtained by $I_{b-ref} = P_b/U_b$ and $I_{f-ref} = P_f/\Omega C_t$, where I_{f-ref} indicates the torque current reference of flywheel system under typical vector control, Ω indicates the speed of the flywheel system and C_t indicates the ratio between the electrical torque and the torque current of the flywheel-PMSG.

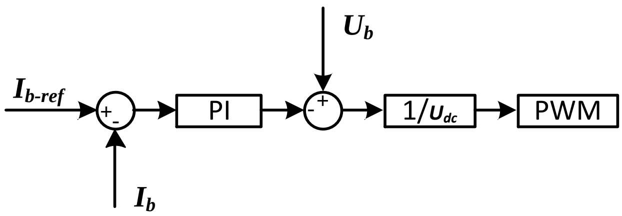

Fig. 2 Control strategy of Bidirectional DC/DC converter

3.1. Normal Mode (M_{NN})

The normal mode is the most usual working mode for the hybrid storage system, where both the battery-array and the flywheel system have the normal SOCs. Because of the intermittence and randomicity of wind power, solar power and the local loads, there is high-frequency power fluctuation in DC bus of the system. The battery-array is not suitable for the high-frequency power fluctuation for its big time constant, so the flywheel system, with its small time constant, can be used to absorb the high-frequency power fluctuation. However, the capacity of the flywheel system is not very big to reduce the cost of the hybrid system, so the battery-array can be used to provide a long-time stable power supply. Accordingly, based on the characteristics of the battery-array and the flywheel system, the proposed control strategy is illustrated as Fig.3.

In both grid-connected and islanded modes, the power references of the battery-array and the flywheel system can be assigned by the control strategy in Fig.3. By regulating the gain factor *K*, the power distribution between the battery-array and the flywheel system can be changed. In the transient process between grid-connected operation and islanded operation, the power balance can also be kept by the fast response of the flywheel system, so the proposed method is also suitable for the transient process.

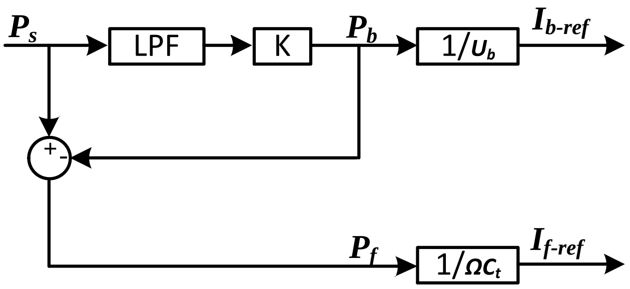

Fig. 3 Block diagram of power in storage system

3.2. Flywheel Abnormal Mode (M_{LN}, M_{HN})

In this mode, the SOC of the battery-array is in normal state, but the SOC of the flywheel system is too high or too low, which will weaken the ability of the whole storage system to absorb or release high-frequency power, even lost the ability completely in the worst situation. Therefore, the storage system is required to change its mode to the normal one as soon as possible to recover its ability and keep the system stable.

In the grid-connected operation, the flywheel system can exchange the power to the utility grid until the SOC returns to normal state, then the control strategy can be changed to the one for normal state. Although the method will involve some impact to the utility grid, the effect of the impact will be very small for the limited power capacity of the flywheel system. The proposed method can work for the stability of the distribute generation system.

In islanded operation, for no power exchange between the storage system and the utility grid, it becomes necessary to keep the power balance in the distributed generation system, where the fast response characteristics of the flywheel system is essential for the stability. Because of the uncertainty of the wind power and solar power, the power exchange between the battery-array and the flywheel system through the DC bus is the key point to the control strategy. For example, when the SOC of the flywheel system is too low, the battery-array will discharge to the DC bus so that the flywheel system can be charged by the DC bus until its SOC returns to the normal state.

3.3. Battery-array Abnormal Mode (M_{NL}, M_{NH})

In this mode, the SOC of the flywheel system is in normal state, but the SOC of the battery-array is too high or too low, which will be harmful for the whole system to work in a long time stably. Therefore, it's required to be controlled to return to the normal state as soon as possible.

In the grid-connected operation, the battery-array can return to its normal state by the strategy which is similar with the one described in 3.2.

In islanded operation, the battery-array is required to be charged by the flywheel system though DC bus. However, it's hard to charge the battery-array to its normal state because of the limited capacity of the flywheel system. Since there is no other energy in the distributed system can be used to charge the battery-array, the control strategy will charge the battery-array by the flywheel system until the system connects to the utility grid again.

3.4. Battery-array and Flywheel System Abnormal Mode (M_{LH}, M_{HL}, M_{HH}, M_{LL})

In the modes of M_{LH} and M_{HL}, the working state of the hybrid system can be changed to one of the working states detailed in 3.1 to 3.3 by the power exchange between the battery-array and the flywheel system though DC bus, no matter the distributed generation system is working in grid-connected operation or islanded operation. And then the system can be controlled by the strategy in 3.1 to 3.3 respectively.

In the mode of M_{HH}, the SOCs of the battery-array and the flywheel system are both too high. In the grid-connected operation, the hybrid storage system can release its extra energy to the utility grid. In the islanded operation, the output power of the wind turbine and the photovoltaic panel will be reduced to some value which is less than the load power, then the power difference between the renewable generation power and the load power will be provided by the hybrid energy storage system. When the hybrid storage system returns to the normal state, the wind turbine and photovoltaic panel will work in MPPT mode again.

In the mode of M_{LL}, the SOCs of the battery-array and the flywheel system are both too low. In grid-connected operation, the hybrid storage system can be charged by the utility grid to its normal state. In islanded operation, if the output power of the renewable generation system in MPPT model is still less than the load power requirement, the unimportant loads will be disconnected to guarantee the normal operation of the important loads and keep the stability of the distributed generation system until more power is outputted by the renewable generation system or the utility power recovers, which is the worst case.

4. SIMULATION AND ANALYSIS

A simulation system illustrated as Fig.1 is built up in Matlab/Simulink. At the beginning, the SOCs of the battery-array and the flywheel system are both in normal states. Under the control strategy in Fig.3, the simulation result is illustrated as Fig.4. The load power is increased from 0.8w to 1.8kw at 2s abruptly and returns to 0.8w at 4s suddenly where *K*=0.9. It can be noticed that the high-frequency power and the low-frequency power are responded by the flywheel system and the battery-array respectively.

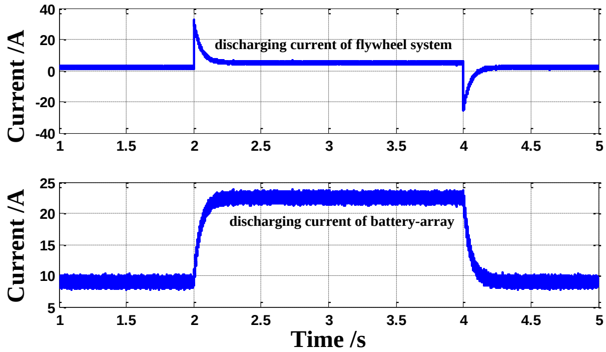

Fig. 4 Currents of storage system in mode of M_{NN}

In the model of flywheel abnormal state, if the SOC of the flywheel system is too low, the flywheel system will still respond to the high-frequency power requirement, and will be charged by the battery-array in idle period to return to the normal state, which is illustrated as Fig.5 and Fig.6.

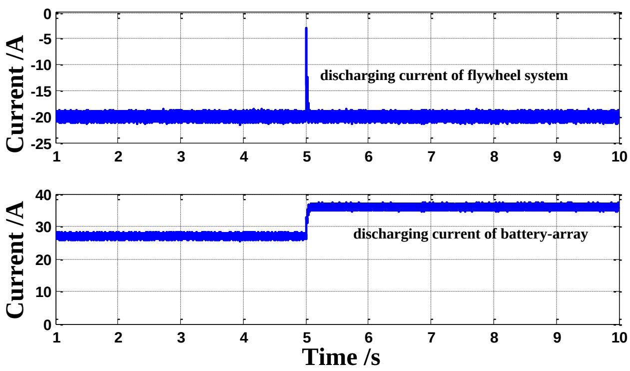

Fig. 5 Currents of storage system in mode of M_{LN}

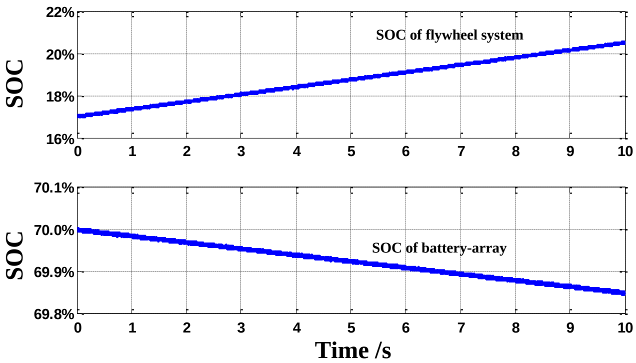

Fig. 6 SOC of storage system in mode of M_{LN}

In Fig.5 and Fig.6, it can be known that, at the beginning, the SOC of the flywheel system is 17%, which indicates the flywheel system is in low state. Then the system is working under the proposed strategy. It can be noticed that the battery-array provides the power not only for the loads but also for charging the flywheel system though DC bus. At 5s, a power fluctuation occurs, then the control strategy is applied as Fig.3. After the fluctuation, the battery-array will continue to charge the flywheel system to its normal state.

The simulation results of the hybrid storage system in the modes of battery-array abnormal states are similar with the ones while the flywheel system is in abnormal states. In the modes of M_{HH} and M_{LL}, it requires to switch off MPPT and cut off the unimportant loads as discussed in above sections.

5. CONCLUSIONS

In this paper, the working modes of the hybrid energy storage system, which consists of the battery-array and the flywheel system and used in the distributed generation system with hybrid bus structure, are classified into different groups according to the SOCs of the storage units. For each working mode, the different control strategy is applied to keep the power balance of the distributed generation system, reduce the impact to the utility power and realize the islanded operation. By the control of the bidirectional DC/DC converter and the flywheel-side converter, a proposed novel energy management strategy is achieved. The simulation results and analysis verify the effectiveness of the proposed strategy.

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