A three-level support method for smooth switching of the micro-grid operation model

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Abstract. Smooth switching of micro-grid between the grid-connected operation mode and off-grid operation mode is one of the key technologies to ensure it runs flexible and efficiently. The basic control strategy and the switching principle of micro-grid are analyzed in this paper. The reasons for the fluctuations of the voltage and the frequency in the switching process are analyzed from views of power balance and control strategy, and the operation mode switching strategy has been improved targeted. From the three aspects of controller's current inner loop reference signal, voltage outer loop control strategy optimization and micro-grid energy balance management, a three-level security strategy for smooth switching of micro-grid operation mode is proposed. From the three aspects of controller's current inner loop reference signal tracking, voltage outer loop control strategy optimization and micro-grid energy balance management, a three-level strategy for smooth switching of micro-grid operation mode is proposed. At last, it is proved by simulation that the proposed control strategy can make the switching process smooth and stable, the fluctuation problem of the voltage and frequency has been effectively improved.

1. Introduction
As an effective way to deal with the large-scale clean energy access to the power grid and ensure the efficient operation, the micro-grid technology has become one of the research hotspot in the field of academic and engineering application. It is also one of the important content of the construction of strong smart grid in China.

The on-line model and the island model are two kinds of typical operation models of a micro-grid. Under a normal condition the micro grid in the on-line state could operate according to the dispatch instructions that send power to the main grid or accept power from the main grid or keep self-balance. When there is a fault or a special case in the main grid, the micro-grid need to switch to the island model. This is the key process that guarantee the power supply continuity, the reliability and the high-power quality of the micro-grid. It is also the key point and the difficult point of the micro-grid technology research.

At present, scholars have carried out some researches on the smooth switching technology of the micro-grid operation mode, which include: fast islanding detection method [1-3], load shedding strategy after islanding [4,5], switching strategy of forced commutation [6-9], controller parameter optimization method, controller state following strategy, etc. These studies, from different angles,
have improved the switching process to some extent, but it is difficult to make the switching process completely smooth.

There are many reasons for the fluctuation of voltage and frequency during the switching process [10-14]. To solve the problem of switching fluctuation fundamentally, comprehensive protection measures should be taken. This paper makes a comprehensive analysis of the cause of the switching process fluctuations, the smooth switching method of micro-grid operation model is studied from the three aspects of controller's current inner loop reference signal tracking, voltage outer loop control strategy optimization and micro-grid energy balance management.

2. The operation mode and control strategy of micro-grid

The micro-grid structure used in this paper is shown in figure 1. The three micro power sources are simulated by a DC source and a voltage source inverter. The load is consisted of RLC load and motor load. The micro grid control system is divided into system level control (micro-grid power and load management) and local level control (the output control of micro power sources). When the micro-grid run in an on-line state, the PQ control strategy is adopted by the micro power source, and the output of the micro sources are adjusted according to the instructions of the system level control. When the micro-grid switch to the island model, it could adopt the master-slave control model (VF-PQ), peer control mode or droop control method etc. The master-slave control strategy is simple and effective. In this paper, the master-slave control strategy is applied to the micro-grid control system in the island condition.

![Figure 1. the micro-grid structures](image)

The double loop structure based direct current control method is used in the controller of each micro power source, which has fast current response characteristics and inherent current limiting capability. And it is widely used in engineering. To eliminate the steady-state error, the controller of voltage loop adopts PI control, the control block diagram is shown in Figure 2. Where Pref and Qref are respectively the active power reference value and the reactive power reference value of the converter. Pa and Qa are respectively the converter outlet detection value of the active power and reactive power. Udref and Uqref are the reference voltage of D component and Q component respectively. Idref and Iqref are the current loop reference value.
Figure 2. The control block diagram of the voltage loop

The block diagram of the current inner loop is shown in Figure 3. The $I_{sd}$, $I_{sq}$, $U_{sd}$ and $U_{sq}$ in the figure are respectively the output current and voltage signals of the converter, the $d$ axis component and the $q$ axis component. $L$ is the reactor inductance value. $\omega$ is the angular frequency.

Figure 3. the block diagram of the current inner loop

3. Analysis of the fluctuation in the switching process of the micro-grid operating model

Under the master-slave control strategy one or several sources are selected as the master source, for which VF control strategy is selected to provide voltage and frequency support for the micro-grid. The other micro source is slave source which adopt the PQ strategy. In this paper the source 1 is selected as the master source and the source 2 and the source 3 are selected as the slave sources. When there is fault in the main grid, the micro-grid could cut from the main grid and run in an island model. The master source would switch to the VF strategy from the PQ strategy after about 0.1-0.2 seconds, during which the islanding detection system would confirm the island condition. And then the micro-grid has switched to the island model from the on-line model.

It is shown in the first section that there is a difference in the outer voltage loop between the PQ control strategy and VF control strategy, and they have a same current loop structure. It could be get through the simulation that when main circuit structure of the converter constant, PQ inner current control strategy and VF control strategy can use the same PI controller. Therefore, when the master source is switched from the PQ control strategy to the VF control strategy, only the reference signal and the synchronization signal of the current loop need to be switched.

From the viewpoint of the power balance of the micro-grid there are two states when the micro-grid switch from the on-line model to the island model, that are power balance state (when the power on the tie line is 0) and power imbalance state (when the power on the tie line is not 0). The simulation examples are carried out to analyze the two situations.

Example 1
The simulation conditions when the power is imbalance in the micro-grid are shown as following. The capacity of the source 1 is 15kW/6kVar. The RLC load in bus 1 would input at 0.2s whose capacity is 25kW/16kVar. The capacity of the source 2 is 12kW/7kVar. The motor load in bus 2 would input at 0.4s whose capacity is 25kW/16kVar. The capacity of the source 3 is 8kW/6kVar. The RLC load in bus 3 would input at 0.6s whose capacity is 25kW/16kVar. At the time 1s the micro-grid cut off from the main grid, and at the time 1.1s the island condition is confirmed and the control strategy changed. The simulation results of the process are shown as figure 4.
Example 2

The simulation conditions when the power is balance in the micro-grid are shown as following. The capacity of the source 1 is 15kW/6kVar. The RLC load in bus 1 would input at 0.2s whose capacity is 25kW/6kVar. The capacity of the source 2 is 12kW/10kVar. The motor load in bus 2 would input at 0.4s whose capacity is 16kW/10kVar. The capacity of the source 3 is 8kW/6kVar. The RLC load in bus 3 would input at 0.6s whose capacity is 8kW/6kVar. At the time 1s the micro-grid cut off from the main grid, and at the time 1.1s the island condition is confirmed and the control strategy changed. The simulation results of the process are shown as figure 5.
If the power is imbalance in the micro-grid when it cut from the main grid, the voltage and frequency of the micro-grid could be stocked, that could be get by the result shown in figure 4 and it is easy to be understood. While, it is shown by figure 5 that the voltage and frequency also fluctuate violently when the power is balance in the micro-gird. Therefore, the power imbalance is not the only reason causing the voltage and frequency fluctuation in the switching process.

In the second simulation, the output of the source shouldn't have changed when the operation mode switch, due to the micro-grid internal power is balanced. But the result in figure 5 shows that in the process of switching, the active power and reactive power output of the master source generated large fluctuations. This phenomenon shows that in the switching process the current loop reference signals of the master source controller had a big change, this is undesirable. To find the root cause, the main power supply voltage loop controller is analyzed. It is shown in figure 2 that the outer loop controllers of the voltage PQ control and VF control both adopt PI controller. In grid on-line condition, the VF voltage outer loop controller in the open-loop standby state, and its output signal could not keep consistent with the output signal of the PQ voltage outer loop controller. That cause the current loop reference signal generating a step change in the switching process, which lead to the voltage and frequency fluctuation. This problem exists in the process when the micro-grid switching from island mode to the on-line mode.

The mismatch of the control model during islanding detection process is the third cause of voltage and frequency fluctuations during switching process. During the island detection process after the micro-grid cutting from the main grid, all the sources in the micro-grid remain PQ control that could not provide the frequency and voltage support for the micro-grid. If the micro-grid is in an unbalanced state before the islanding, or in the meantime the micro-grid is subject to changes in load, etc., a deterioration in the voltage and frequency quality of the system would be led to.
4. A three-level support method for smooth switching of the micro-grid operation model

Be aimed at the problems shown above, a three-level support method for smooth switching of the micro-grid operation model is proposed consider the three aspects of controller’s current inner loop reference signal tracking, voltage outer loop control strategy optimization and micro-grid energy balance management.

(1) The reference signal following method for the controller inner loop

To solve the signal following problem of the standby voltage outer loop controller the feedback control structure with a PI controller is designed to eliminate the error between the signals of the VF outer loop and the PQ outer loop. The diagram of the modified voltage outer loop controller is shown in Figure 6.

![Figure 6. The diagram of the modified voltage outer loop controller](image)

The function of the SELECT block in the diagram is to select the output signal between the two input signals according to the control strategy select signal $s$.

(2) Optimization of the micro source control strategy

In this paper an optimized PQ control strategy is proposed to make up for the shortcomings of traditional PQ control strategy. In the optimized PQ control strategy, the reference values of $P$ and $Q$ would be corrected when the voltage and frequency deviation exceeds a certain limit. Thereby the system voltage and frequency are supported. The control strategy block diagram is shown in figure 7.

![Figure 7. The diagram of the optimized PQ control strategy](image)

Where: $f_{ref}$ is the reference value of the frequency. $f$ is the measurement value of the frequency. $U_{ref}$ is the reference value of the voltage. $U_s$ is the measurement value of the frequency. The function of the OCOL-f controller is to optimize the increment of the reference value of the frequency. When the frequency difference in the threshold range, which is set to ±0.2Hz in this paper, the output is 0, when the frequency difference beyond the threshold range, the output is the difference itself. The controller has a similar function to optimize the increment of the reference value of the voltage.

(3) The micro-grid energy balance management strategy

Under the power imbalanced condition, the voltage and frequency fluctuation will inevitably occur when islanding occurs.

If the power imbalance is within the scope of the master source regulation, the voltage and frequency fluctuation of the micro-grid can be suppressed and restored to normal level through
regulation of the master source. However, when the power imbalance exceeds the capacity of the master source, the micro-grid will not guarantee frequency and frequency quality. Then, the micro-grid system layer control strategy is required to issue instructions to adjust the output power of each subordinate micro power source, to restore the internal power balance of the micro-grid as soon as possible to ensure the power quality level.

In this paper an energy balance management strategy for the micro-grid is proposed, the control flow is shown in figure 8.

![Figure 8. the control flow of the energy balance management strategy](image)

Where: $P_L$ is the detection power on the tie line. $PB$ is the total reserve in the micro-grid. It should be noted that the principle of load shedding considering that as little as possible to make the micro-grid load shedding. And the higher the importance of load is, the lower removal priority is.

4 Simulation analysis

In this paper, simulation examples are carried out to prove the effectiveness of the proposed control strategy.

(1) Example 3

The simulation conditions are the same as the simulation conditions of example 2 in section 2. The control strategy adopts the strategy proposed in section 3. The simulation results are shown in figure 9.

![Simulation Results](image)
It is shown from the figure 5 and Figure 8 that the voltage fluctuation is almost zero, the frequency fluctuation is smaller than 0.1Hz and the output of the micro sources are kept stable. It is proved that the function of the feedback loop between the external loop controller eliminates the error of the reference value of the current, and, in the strategy proposed in this paper the switching process under a power balance condition could remain stable and smooth.

(2) Example 4

The simulation conditions are the same as the simulation conditions of example 1 in section 2. The control strategy adopts the strategy proposed in section 3. The simulation results are shown in figure 10.
Figure 10. the simulation result of example 4
It is shown in the figure 10 that there is a power imbalance of 10kW, 5kVar, which is shown as the tie line power, in the micro-grid. After the island, frequency and voltage fluctuation are emerged due to the power imbalance of the micro power grid. When fluctuations beyond the limits, the optimizing controller is activated, additional active power and reactive power are called out to adjust the voltage and the frequency of the micro-grid. At the same time, the source 2 received the power adjust instruction and add the output of active power and reactive power. Under the combined action of these measures, the power balance in the micro-grid is promoted, and the restoration of voltage and frequency is accelerated.

5. Conclusion
In this paper, the switch process of the micro-grid operation model is analyzed, and three level support method for smooth switching of the micro-grid operation model are studied. The conclusions are get as following.

(1) There are 3 reasons for the voltage and frequency fluctuations during switching process: the mismatch of the control model during islanding detection process, the output signal of the standby voltage outer loop controller could not follow the one that is used, and the mismatch of the control model during islanding detection process.

(2) The three-level support method for smooth switching of the micro-grid operation model proposed in this paper could effectively improve the fluctuation problem of the voltage and frequency and make the switching process smooth and stable.

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