Research on Multi-mode Operation Control Strategy of Feeder Flexible Interconnection in Distribution Network Based on Flexible Multi-State Switch

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Abstract. Aiming at the problems of multi-mode operation and switching, unbalanced feeder load and heavy load of main transformer in flexible interconnection system of distribution network based on Flexible Multi-State Switch (FMSS), a multi-mode operation control strategy of feeder interconnection in distribution network based on Virtual Synchronous Generator (VSG) is proposed, which includes load balancing control strategy and heavy load main transformer automatic control strategy. Firstly, according to the feeder and main transformer load status, the operation mode of system is divided. Then, through the analysis power transmission and switching logic of different operating mode, active power control instructions of FMSS under multi-mode operation are obtained. So that multi-mode stable operation and free switching of the system, the feeder load balancing and main transformer heavy load automatic regulation are realized. In addition, there is no need for control strategy switching. Simulation verifies the rationality and effectiveness of the proposed control strategy.

1. Introduction

Under the background of the current power supply mode of "closed-loop design and open-loop operation" of distribution network (DN), with the large-scale high-penetration access of distributed energy (DG), such as solar and wind energy [1], the security and stability of DN has become increasingly problematic. Due to the intermittent and random nature of DG, it is easy to cause feeder load imbalance. If the power flow is not actively regulated, it may also lead to heavy load of the main transformer, seriously threatens the safe and stable operation of the grid [2]. Therefore, the flexible interconnection technology of the DN based on FMSS has received extensive attention [3].

FMSS is the key equipment to realize the flexible interconnection of feeders in DN. It has many advantages such as fast response speed, flexible control method, and high switching frequency. It has significant advantages in enhancing DG consumption, balancing feeder load, and improving the reliability of power supply [4]. In recent years, scholars have made a great deal of research on the operation control strategy of feeder interconnection in DN based on FMSS. At present, the research on operation control of FMSS mainly focuses on system optimization based on constant-voltage and constant-power control in a single mode. However, FMSS has multiple operation modes when the DN feeders are interconnected. It is necessary to study multi-mode operation control strategy of FMSS.
Ref. [5] proposed the FMSS switching control and the adaptive recovery control strategy considering the failure operation mode, but the feeder load balancing was not considered. In order to realize the multi-mode operation of FMSS, a model predictive cooperative control strategy is proposed in [6], but the calculation is too complicated. However, FMSS adopts constant-voltage and constant-power control in the above studies, and it needs to switch the control strategy during multi-mode operation, which increases the complexity of the controller. Ref. [7] points out that the FMSS control strategy based on VSG can realize the switching between different operating modes, but feeder load balancing was not considered. On the other hand, current research mainly focuses on FMSS equipment, with less attention pay to the FMSS multi-mode operation control with energy storage. Ref. [8] pointed out that FMSS with energy storage is more flexible in regulation than FMSS, but it may cause main transformer overload during multi-mode operation.

In summary, this study takes the DN feeders flexible interconnection system based on FMSS with energy storage as the research object, deeply analyses the system operation mode and the power transmission balance relationship and switching logic in different modes. Load balancing control strategy based on VSG and automatic control strategy of main transformer heavy load are proposed, the strategy realizes the feeder load balancing and automatic control of main transformer heavy load while achieving stable multi-mode operation and free switching of the system. And there is no need to switch control strategies. The simulation proved the effectiveness of the control strategy.

2. Flexible interconnection system for distribution network

As shown in Figure 1, it is a flexible interconnection system of DN feeders with two feeders interconnected. Multiple converters in the system are cascaded back to back through the 750V DC bus, FMSS is installed at the ends of feeders 1 and 2 for feeder interconnection, which contains 4 ports: AC ports 1, 2 and DC ports 1, 2. DC port 1 converter uses Boost topology to realize flexible access to DGs. DC port 2 converter uses dual active bridge (DAB) topology to connect the battery to provide support for energy interaction and achieve DC bus voltage stability and flexible regulation.

![Figure 1. Flexible interconnection system of distribution network.](image)

3. System operation mode and power transmission analysis

3.1. System operation mode

According to the different state of FMSS port on/off-grid, the system operation mode is divided into three types: ① flexible interconnection operation mode; ② load transfer operation mode; ③ island operation mode. The specific description is as follows:

3.1.1. Flexible interconnection operation mode.

In this mode, the VSC1 and VSC2 ports of FMSS are all connected to the grid. Feeders 1 and 2 are connected through two ports. Feeder power can be controlled by VSG to achieve bidirectional flow. The DC bus voltage is controlled by the energy storage DAB, and the DGs is controlled by MPPT. In addition, reactive power compensation can be carried out according to upper instruction.
3.1.2. Load transfer operation mode.
In this mode, an AC port of FMSS is off-grid due to a certain DN failure. In this situation, the fault feeder load must be transferred through FMSS to achieve reliable power supply. Whether it is on-grid or off-grid, the AC port of FMSS is always controlled by the VSG without switching control strategies.

3.1.3. Island operation mode.
In this mode, two AC ports of FMSS are both off-grid. At this time, DGs provides short-term emergency power supply for the important feeder loads. DAB provides short-term energy support for system operation while maintaining the DC bus voltage regulation. When the DN is restored, the system will work in mode ① or ② again. Although the above three types of operating modes are classified according to the system of this article, the classification has universal applicability.

3.2. Power transmission analysis
In this paper, $P_{ac1}$ and $P_{ac2}$ are the feeder power of DN 1, 2 respectively, $P_{VSC1}$ and $P_{VSC2}$ are the port power of VSC1 and VSC2 respectively, $P_{pv}$ is the power generated by the photovoltaic array, $P_{bat}$ is the charging and discharging power of the battery, $P_{aL1}$ and $P_{aL2}$ are AC load power of feeder 1 and 2 respectively, $P_{dl}$ is the DC load power, and $S_T$ is the rated capacity of T1 and T2. Assuming that the power flowing into the DN is positive, the power flowing out of the AC port is positive, and the battery charging power is positive. In addition, $P_{net1}$, $P_{net2}$, and $P_{net3}$ are defined as the critical power of the system in three types of operating modes ①, ②, and ③. The expression is as follows:

$$
\begin{align*}
P_{net1} &= 1.6S_T + P_{pv} - (P_{aL1} + P_{aL2} + P_{dl}) \\
P_{net2} &= 0.8S_T + P_{pv} - (P_{aL1} + P_{aL2} + P_{dl}) \\
P_{net3} &= P_{pv} - (P_{aL1} + P_{aL2} + P_{dl})
\end{align*}
$$

(1)

where, $P_{net1}$=0 indicates the maximum load that can be supplied when the two main transformers are critically loaded in the ① operation mode. $P_{net2}$=0 indicates the maximum load that can be supplied by the main transformer under critical heavy load in the ② operating mode. $P_{net3}$=0 indicates the maximum load that the system can be supply in the ③ operating mode.

Assuming that the initial state of the battery is full, its charge and discharge thresholds are SOClmin and SOClmax, which are set to 20% and 80%, respectively. The reason for introducing the state of charge SOClbat is to prevent the battery from overcharging and overdischarging.

4. System operation control strategy

4.1. Load balancing control strategy
In order to overcome the drawback of the traditional load balancing control strategy, this paper takes the three-feeder interconnection system as an example to derive the load balancing control strategy, which is also applicable to the flexible interconnection system shown in Figure 1. The proposed control strategy takes into account both normal and fault conditions and has wide applicability.

Figure 2. normal operation.                                Figure 3. N-1 fault operation.

As shown in Figure 2, the system is operating normally. When the load power of the feeder $i$ is less than the average value $\frac{1}{n} \sum_{i=1}^{n} P_{dl}$ of the load power of the n feeders, in other words, the feeder $i$ is
relatively light loaded, the “±” in equation (2) is taken to be positive, indicating that the port connected to the feeder \( i \) absorbs power, which is equivalent to adding the feeder. Vice versa, Through the above regulation strategy, the feeder load balance during normal operation of the DN can be realized.

\[
\begin{align*}
    P_{\text{net}} &= P_{\text{al},i} \pm P_{\text{VSC},i} \\
    P_{\text{VSC},i} &= \left| P_{\text{al},i} - \frac{1}{n} \sum_{i=1}^{n} P_{\text{al},i} \right|
\end{align*}
\]  

(2)

As shown in Figure 3, when the system fails N-1, the regulation is as follows:

\[
\begin{align*}
    P_{\text{VSC},i} &= P_{\text{al},i} \\
    P_{\text{al},j} &= P_{\text{al},j} + P_{\text{VSC},j} \\
    P_{\text{VSC},j} &= \left| \frac{1}{n-1} \sum_{i=1}^{n} P_{\text{al},i} - P_{\text{al},j} \right|
\end{align*}
\]  

(3)

When the feeder \( i \) fails, the load of the faulted feeder is all supplied by the non-faulty feeder, and the load of the non-faulty feeder is balanced, that is, equation (3) is satisfied. Through the above regulation strategy, the feeder load balance in the case of N-1 failure in the DN can be realized. This strategy is suitable for the load balance regulation of three or more feeders.

4.2. Load balancing control strategy

In order to overcome the main transformer overload problem that may occur in the multi-mode operation of the system, it is necessary to perform power flow control on the overloaded main transformer to make it out of the overload. For this reason, this article proposes the regulation of a certain main transformer \( T_i \) under heavy load, the regulation is as follows:

When the system is in ① operating mode, if \( P_{\text{net}1} \geq 0 \), the critical power of the system is redundant, then:

\[
\begin{align*}
    P_{\text{VSC},i} &= P_{\text{al},i} - 0.8S_T (\text{SOC}_{\text{bat}} < \text{SOC}_{\text{min}}) \\
    P_{\text{VSC},i} &= P_{\text{al},i} - \frac{P_{\text{al},i} + P_{\text{al},j} - P_{\text{al},i}}{2} (\text{SOC}_{\text{bat}} \geq \text{SOC}_{\text{min}})
\end{align*}
\]  

(4)

if \( P_{\text{net}1} < 0 \), the critical power of the system is deficiency, then:

\[ P_{\text{VSC},i} = P_{\text{al},i} - 0.8S_T \]

(5)

When the system is in ② operating mode, if \( P_{\text{net}2} \geq 0 \), the critical power of the system is redundant, then:

\[
\begin{align*}
    P_{\text{VSC},i} &= P_{\text{al},i} - 0.8S_T (\text{SOC}_{\text{bat}} < \text{SOC}_{\text{min}}) \\
    P_{\text{VSC},i} &= P_{\text{al},i} - P_{\text{al},j} - P_{\text{al},i} (\text{SOC}_{\text{bat}} \geq \text{SOC}_{\text{min}})
\end{align*}
\]  

(6)

if \( P_{\text{net}2} < 0 \), the critical power of the system is deficiency, then:

\[ P_{\text{VSC},i} = P_{\text{al},i} - 0.8S_T \]

(7)

According to the above analysis, in order to realize the stability and free switching of the system in multi-mode operation, while realizing feeder load balancing and automatic regulation of heavy-load main transformers. Figure 4 shows the overall regulation strategy of the system.
5. Simulation verification and analysis
In order to verify the effectiveness of the proposed control strategy, the Simulink simulation model of the system was established, and three operating modes were simulated. The system parameters are: \( S_T = 100 \text{kVA} \); rated capacity of FMSS: 50kVA; rated power of Boost: 30kW; \( P_{dL} = 5 \text{kW} \); \( P_{pv} = 25 \text{kW} \).

5.1. Flexible interconnection operating mode simulation
The simulation scheme is set as follows: a) \( t = 0.2 \sim 0.5 \text{s} \), \( P_{aL1} = 40 \text{kW} \), \( P_{aL2} = 20 \text{kW} \), \( T_1 \) and \( T_2 \) are normally loaded. b) \( t = 0.5 \sim 1.0 \text{s} \), \( P_{dL} \) increases by 50kW to 90kW, \( T_1 \) is heavy load. c) \( t = 1.0 \sim 1.5 \text{s} \), \( P_{dL} \) increases by 70kW to 90kW, \( T_1 \) and \( T_2 \) are heavy load. The simulation results are shown in Figure 5.

The simulation results show that relying on the proposed regulation strategy, when the system is running and switching between multiple modes in ① mode, the system can maintain the total power balance and feeder load balancing through FMSS, and the \( U_{dc} \) is always stable at 750V.

5.2. Load transfer operating mode simulation
The simulation scheme is set as follows: a) \( t = 0.2 \sim 0.5 \text{s} \), the system operation mode is the same as before. b) \( t = 0.5 \sim 1.0 \text{s} \), \( T_2 \) is out of service. c) \( t = 1.0 \sim 1.5 \text{s} \), \( P_{aL1} \) increases by 50kW to 90kW, \( T_1 \) is heavy load. The simulation results are shown in Figure 6.

The simulation results show that relying on the proposed regulation strategy, when the system is running at fault in ② mode, the system can realize load transfer and main transformer off heavy load to improve the reliability of system power supply through FMSS, and the \( U_{dc} \) is always stable.
5.3. Island operating mode simulation

The simulation scheme is set as follows: a) \( t=0.2\sim0.5\)s, \( P_{aL1}=30\)kW, \( P_{aL2}=20\)kW, \( T_1 \) and \( T_2 \) are normally loaded. b) \( t=0.5\sim1.5\)s, \( T_1 \) and \( T_2 \) are out of service.

The simulation results are shown in Figure 7. The simulation results show that relying on the proposed regulation strategy, when the system is on an island in \( \textcircled{3} \) mode, the system can realize emergency power supply for important fault loads to improve power supply reliability through FMSS.

6. Conclusion

To the problem mentioned above, this paper proposes a load balancing and heavy load main transformer automatic control strategy based on VSG. The simulation results prove that the proposed control strategy can make the system operate stably and freely switch between multiple modes, realize the feeder load balance and the heavy load main transformer to get rid of the heavy load, and effectively improve the power supply safety and economy of the DN.

Acknowledgment

Thanks to the Hunan Provincial Department of Education project(19C0531) for funding this research.

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