Flexible Multi State Switch of Distribution Network Based on Flux Controlled Adjustable Reactor

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Abstract. Flexible Multi-states Switch based on power electronics technology can realize the flexible interconnection between feeders, elastically control feeder power flow and solve the serious unbalance of feeder power flow in the distribution network. To solve the problem, this paper proposes that using flux-controlled variable reactor as the topology of flexible multi-states switch in distribution network. Firstly, flux-controlled variable reactor’s principle will be introduced; Then, we analyze the principle of feeder power flow’s control using variable reactor; After that, the control strategy for the flexible multi-states switch with different access methods is proposed; At last, a MATLAB simulation model and the prototype experiment platform are built. The results verified the power flow control function of flexible multi-states switch and effectiveness of proposed controlled strategy.

1. Introduction

The characteristics of "closed-loop design and open-loop operation" of traditional distribution network, the continuous penetration of distributed new energy, the diversification of user load and other practical problems make the two-way power flow, unbalanced feeder load, voltage exceeding limit and other problems of distribution network increasingly prominent. As a new type of flexible primary equipment, flexible multi-state switch based on power electronic technology can partially replace the traditional interconnection switch in the distribution network, has gradually become a hot spot in the field of active distribution network research[1].

Among many flexible multi-state switching topologies, the ones based on series impedance FACTS[2], such as Thyristor Switched Series Capacitor(TSSC)[3], Thyristor Controlled Series Capacitor(TCSC)[4] and GTO Controlled Series Capacitor, (GCSC)[5], are suitable for small capacity active power regulation due to their low cost and loss, but they also have small regulation range and generate harmonics Wave pollution and other issues.

At present, a series of research work has been carried out on the application of flexible multi state switch in distribution network at home and abroad, but the topology, principle analysis, control method and other aspects of the device still need further research. In this paper, based on the traditional impedance facts and flux controlled adjustable reactor, a new topology of flexible multi state switch device for distribution network is proposed. Its working principle is analyzed and its control strategy is proposed. The software simulation and experimental verification are carried out.
2. System modeling analysis

2.1. Principle analysis of flux controlled adjustable reactor

Figure 1 is the structure diagram of flux controlled adjustable reactor. Figure 2 is the T-type equivalent circuit of the adjustable reactor. Among them, the leakage impedance of the working winding is $Z_1$; the leakage impedance converted from the control winding to the working winding side is $Z_2'$ and the excitation impedance of the reactor is $Z_m$. We make the turn ratio $K$ of the working winding and the control winding of the special reactor 1:$K = \frac{N_1}{N_2}$.

\[
\begin{align*}
 u_1 &= Z_1i_1 + Z_2i_0 = Z_1i_1 + Z_m(i_1 + i'_2) \\
 u'_2 &= Z_2'i_2 + Z_2i_0 = Z_2'i_2 + Z_m(i_1 + i'_2)
\end{align*}
\]

By controlling the output of the inverter and substituting $i'_2 = \alpha i_1$, we can get

\[
Z_{AX} = u_1 / i_1 = Z + (1 + \alpha)Z_m
\]

Because the excitation impedance of the reactor is usually much greater than the leakage impedance of the working winding, so the leakage impedance can be ignored. We can get the equivalent impedance value of the reactor is linearly related to the control coefficient $\alpha$. By changing the coefficient, the equivalent impedance can be changed.

![Figure 1. Structure of flux controlled adjustable reactor.](image1)

**Figure 1.** Structure of flux controlled adjustable reactor.

**Figure 2.** T-type equivalent circuit of reactor.

2.2. Power flow control principle of flexible multi state switching device

The reactive power is usually controlled by local compensation. Figure 3 shows the equivalent circuit and vector diagram of feeders with parallel flexible multi-state switching devices. The voltage source vectors of the two feeders are $E_1\angle \delta_1$ and $E_2\angle \delta_2$ respectively; The equivalent impedance of the adjustable reactor is $Z_{AX} = Z \angle \delta$ and the flow current of the flexible multi-state switch device is $i_0$.

\[
\begin{align*}
 E_1\angle \delta_1 &= R + jX_1(Z \angle \delta) \\
 E_2\angle \delta_2 &= R + jX_2(Z \angle \delta)
\end{align*}
\]

![Figure 3. Feeder equivalent circuit and vector diagram with parallel flexible multi state switch device.](image2)

**Figure 3.** Feeder equivalent circuit and vector diagram with parallel flexible multi state switch device.

It can be concluded that the active power injected by the upper feeder to the connection point is
\[ P_i = \text{Re}(V_i \angle \delta_i \cdot I_i) = \frac{V_i^2}{Z_i} \cos \delta_i \]

The active power consumed by the load of the upper feeder is
\[ P_{z_i} = \text{Re}(V_i \angle \delta_i \cdot I_i) = \frac{V_i^2}{Z_i} \cos \theta_i \]

The active power consumed by the reactor is
\[ P_{z_{as}} = \text{Re} \left( \left[ V_i \angle \delta_i - V_i \angle \delta_j \right] \cdot I \right) = \frac{V_i^2}{Z_i} \cos \delta_i \]

Thus, it can be concluded that the active power transmitted between feeders by flexible multi state switching device is
\[ P_{tr} = P_{z_i} - P_{z_{as}} = \frac{V_i^2}{Z_i} \cos \delta_i - \frac{V_i^2}{Z_i} \cos \delta_j \]

If the resistance part of the equivalent impedance of the adjustable reactor is ignored, the active power transmitted by the flexible multi-state switch device is
\[ P_u = \frac{V_i^2}{Z_i} \sin(\delta_i - \delta_j) \]

Figure 4 shows the equivalent circuit diagram and vector diagram of the feeder when the head end of the lower feeder is connected in series with the flexible multi state switch device and the feeder ends are directly interconnected.

Similarly, the active power transmitted by the flexible multi state switch device is
\[ P_u = \frac{E_i E_j \sin(\delta_i - \delta_j)}{Z} \]

Figure 4. Equivalent circuit and vector diagram of feeders with series flexible multi state switching devices.

Assume that the active load of the feeder load below is
\[ P_2 = \frac{E_2^2}{Z_2} \cos \theta_2 \]

Then the active power flow between two feeders is
\[ P = P_1 - P_2 = \frac{E_1 E_2 \sin(\delta_i - \delta_j)}{Z} \]

According to the above analysis, whether the adjustable reactors are arranged in series or in parallel, the flexible interconnection between feeders can be realized.
3. Control strategy

The flexible multi state switching device is controlled according to the power flow transfer command. For series and parallel devices, figure 5 is the voltage and current double closed-loop control strategy proposed in this paper.

![Control strategy diagram](image)

**Figure 5.** Control strategy of parallel flexible multi state switchgear and series flexible multi state switchgear.

Among them, the control goal of voltage loop is to keep the DC side voltage constant, and the current loop carries out current tracking control. The instruction value $i_2^*$ is composed of two parts. One part of $i_{2 ref}$ corresponds to the fundamental current $i_1$ flowing through the working winding of the reactor, so as to realize the regulation of reactance value. The reactance control coefficient $\alpha$ is calculated according to the regulation target of power flow; the other part is $I_{P_ ref}$, which is the difference between the voltage instruction value $U_{dc^*}$ and the feedback value $U_{dc}$ at the DC side, which is adjusted by PI and then combined with the phase obtained by the voltage lock-in of the power grid, so as to maintain the constant voltage at the DC side by controlling the output of the active component of the inverter.

4. Simulation verification and experimental verification

In this paper, a flexible multi state switch simulation model based on adjustable reactor is built in MATLAB simulation software. It is defined that the upper feeder is grid 1, the lower feeder is grid 2, grid 1 is in no-load operation from 0 to 0.5s, the active load is always 10kW after 0.5s, the active load from the initial time of grid 2 to 0.5s is 10kW, the active load from 0.5s to 1s is 20kW, and the active load after 1s is 30kW. The soft opening device is put into use in 0.5s. Figure 6 shows the simulation waveform of active power flow control.

![Simulation waveform](image)

**Figure 6.** Power flow control simulation waveform.

In order to verify the correctness of the proposed flexible multi-state switch topology and the effectiveness of the control strategy, a prototype experiment platform of the flexible multi-state switch principle is built. The device parameters are shown in Table 1.
Table 1. Experiment parameters

| parameter                                      | numerical value |
|-----------------------------------------------|-----------------|
| Supply voltage                                | 7.5V/50Hz       |
| Turn ratio of special reactor working winding and control winding | 1               |
| Leakage inductance of working winding side of special reactor | 0.17mH          |
| Special reactor excitation inductance          | 8.4mH           |
| Grid 1 load                                   | 2 Ω             |
| Grid 2 load                                   | 4 Ω             |
| Inverter switching frequency                  | 10kHz           |
| DC side voltage of inverter                   | 15V             |
| Inverter output filter inductance              | 1mH             |

Figure 7 shows the experimental waveforms of adjustable reactors in parallel or series between feeders. Among them, A2 and A1 are load current waveforms of grid 1 and grid 2 respectively, while A4 and A3 are feeder current waveforms of grid 1 and grid 2 respectively. From the experimental waveform, it can be seen that the feeder current of grid 1 and grid 2 can be basically balanced by the power flow regulation function of flexible multi-state switch devices in parallel between grid 1 and grid 2.

5. Conclusion

As the key equipment, flexible multi state switching device can realize the power flow regulation among multiple feeders. By controlling the flux of the flux controlled adjustable reactor, the impedance value of the reactor can be changed, and then the power flow distribution among feeders can be changed to realize the power flow regulation and control between feeders. It can effectively improve the security and economy of distribution network operation. This paper presents a flexible multi state switching device based on flux controlled adjustable reactor, which has a good effect on the active power flow control of distribution network in steady state. The next step is to carry out research on load transfer, fault isolation and power quality control under the condition of distribution network fault by using flexible multi state switch. The research content of this paper hopes to provide a new idea for the distribution network flexible interconnection power electronic devices.

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