

# Single-phase grounding fault analysis and control scheme of transformerless flexible multistate switch

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**Abstract:** The compact design is suitable for the urban areas with intensive loads. The flexible multistate switch (FMS) can effectively reduce the footprint by removing transformers, which is the development trend of the flexible AC distribution equipment. In PSCAD/EMTDC, a simulation model containing two supply areas embedded in a transformerless FMS is built. Through the single-phase grounding fault simulation under the arc suppression coil grounding, the characteristics of zero-sequence component of FMS are analysed. By means of circuit analysis and sequence component decomposition, the intrinsic mechanism of AC/DC voltage fluctuation in the non-fault supply area caused by the zero-sequence component at the fault area is analysed, and the simulation result is explained. Based on the feeder transformation, a new protection and control scheme is proposed to overcome the problem of the zero-sequence ride through among different supply areas.

## 1 Introduction

The distribution network locating at the end of the power system supplies electricity to power users directly. There are some problems in the distribution network such as the weak grid structure, the low automation level, and so on. With the increasing new power supplies (PV, wind power, etc.) and new loads (electric vehicle, etc.), the voltage fluctuation and feeder power imbalance in the distribution network become more and more serious. However, conventional control measures such as the segment switch and the loop switch cannot effectively solve the problems above [1, 2].

The flexible multistate switch (FMS) is a power electronic device, which is used to replace the traditional loop switch. In addition to the universal switching function, FMS can accurately control the active and reactive power of the feeder line, so as to effectively cope with the stochastic fluctuation caused by distribution supplies and loads [3–5]. The introduction of FMS can completely change the traditional power supply mode of closed-loop design and open-loop operation of the distribution system. The adoption of FMS can avoid the potential security risks caused by switching and greatly improve the fast control capability of the distribution network.

A back-to-back two-terminal or multi-terminal flexible DC distribution system based on the modular multilevel converter (MMC) is one of the available devices for FMS. MMC uses cascaded sub-modules (SMs) to achieve multilevel output with low loss and high reliability, and has been widely used in the

engineering [6, 7]. MMC is usually connected to the AC system using a connection transformer to realise the fault isolation between the AC and DC systems. However, the installation of the connection transformer makes the footprint of FMS greatly increased. FMS is close to the city load centre, so the scarce urban land requires the compact design of FMS, and the transformerless design ought to be considered [8].

Since the connection transformer is removed, the fault characteristic of the distribution system including FMS may be different from the case with the transformer. Here, the common single-phase grounding fault is simulated and analysed, and the internal mechanism is summarised, which can provide technical reference for related engineering and researchers.

## 2 System connection scheme

### 2.1 Connection form

FMS is usually connected to the end of feeder lines and has a variety of system wiring forms: (i) Connect two feeder lines in the same supply area through two converters; (ii) Connect two feeder lines in different supply areas through two converters, as shown in Fig. 1; (iii) Connect multiple feed lines through multiple converters. The wire form of the system with FMS is flexible.

After the integration of FMS, the distribution system combines the characteristics of radial and ring network power supply modes. The benefits are as follows: (i) Balance the load on two feeder lines and improve the power flow distribution capability; (ii) Control the voltage and reactive power and improve the feeder voltage quality; (iii) Reduce power loss and increase economy; (iv) Improve the consumptive ability of distributed power supply; (v) Provide uninterrupted electricity for important loads in case of failure.

### 2.2 Distribution network grounding mode

The grounding mode is a seemingly simple and actually complicated question, which is directly related to the safe operation of the power system. According to the value of the single-phase grounding fault current, the grounding mode can be divided into two types: the large current grounding mode and the small current grounding mode. Among them, the large current grounding mode is always used in the high-voltage transmission field, and the small current grounding mode is fit for the medium-voltage distribution field, which contains the arc suppression coil grounding, the

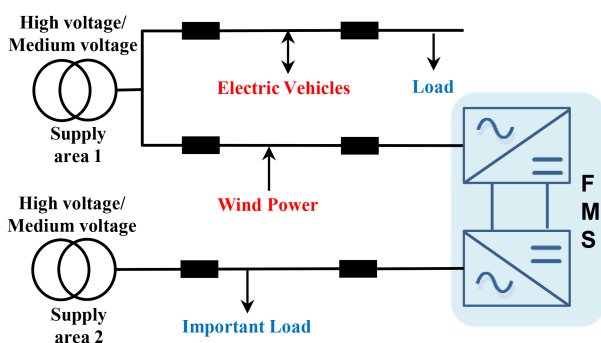


Fig. 1 System connection form of FMS

ungrounded and the large resistance grounding. In the small current grounding mode, the single-phase grounding current is small and the power reliability is high, but the overvoltage level is high and the sustained operation time under the fault state is long, which is easy to damage the system insulation.

In combination with the actual situation and operation experience around the country, at present, the most common grounding modes used for the medium distribution network are the arc suppression coil grounding, especially in the 10 kV voltage level. The arc suppression coil can effectively reduce the grounding current through current compensation, quickly extinguish the fault arc and improve the power supply reliability.

### 3 Simulation study

#### 3.1 Simulation modelling

Fig. 2 shows the schematic diagram of the distribution system with FMS. In two 10 kV power supply areas, loads on the feeder lines are modelled by the static Load model 'Fixed Load' in PSCAD/EMTDC. FMS consists of two half-bridge MMCs (H-MMCs), each arm of H-MMC contains 24 half-bridge SMs (HBSMs) where two HBSMs are redundant. The rated voltage of each HBSM is 0.91 kV. The rated DC voltage of FMS is  $\pm 10$  kV. The rated capacity of each H-MMC is 10 MVA. The two 110 kV power grids, which provide electricity to areas 1 and 2, respectively, adopt the same equivalent short circuit ratio  $SCR = 5$ , and the difference of voltage phase angle is zero. This paper selects 0.78 H as the neutral grounding inductance.

The MMC connected to the area 1 adopts the constant active power and reactive power control strategy. The MMC connected to the area 2 adopts the constant DC voltage and reactive power control strategy. The two MMCs both adopt the inner and outer loop control strategy with the positive-sequence and negative-sequence decoupling function to withstand the overcurrent of power devices under the fault.

#### 3.2 Simulation result

Taking the single-phase grounding fault  $F1$  shown in Fig. 2 as an example, Fig. 3 presents fault response characteristics, where the subgraphs (a)–(d), (f)–(i) present, respectively, the AC current, zero-sequence current, AC voltage and zero-sequence voltage of H-MMCs connected to the areas 1 and 2. Subgraph (e) shows the positive and negative DC voltages, and subgraph (j) shows the neutral current of area 2.

It can be seen from Fig. 3 that in the supply area 1, the voltage of phase A drops to zero quickly after fault, and the voltages of phases B and C increase to 1.73 times of the rated phase voltage. The zero-sequence voltage amplitude is equal to the rated phase voltage. The positive and negative DC voltages contain the fundamental frequency component whose amplitude and phase are the same as the zero-sequence voltage component.

In the supply area 2, the voltage amplitude of phase A is 1.5 kV, the voltages of phases B and C increase to 13.2 and 14.8 kV, respectively, during the fault. The zero-sequence voltage component of area 2 is almost consistent with the area 1.

According to the simulation result, it is obvious that without the transformer, the zero-sequence component will transfer from the fault supply area to the normal operating area through the FMS, and the fault range is expanded. It seems that FMS just like a three-phase conductor for the zero-sequence component. In the 10 kV distribution system with arc suppression coil grounding, the single-phase grounding fault allows the distribution system to operate for extra 2 h temporarily to improve the power supply reliability. If no control measures are taken, the normal operating area will also experience long-term overvoltage, which will increase the probability of other faults due to the long-term overvoltage. Furthermore, the safe and stable operation of the entire distribution system will be affected, and the service life of some devices may shorten.

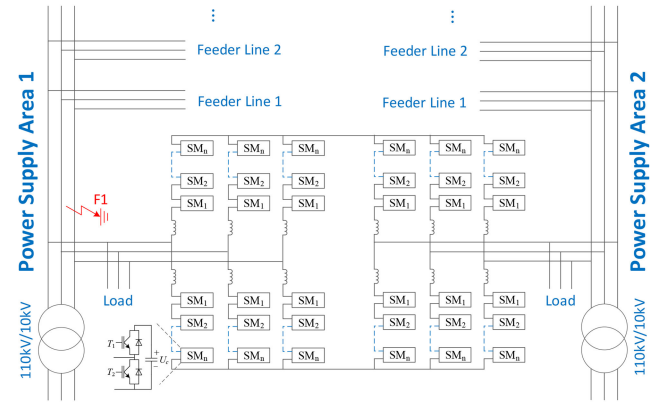


Fig. 2 Schematic diagram of simulation model

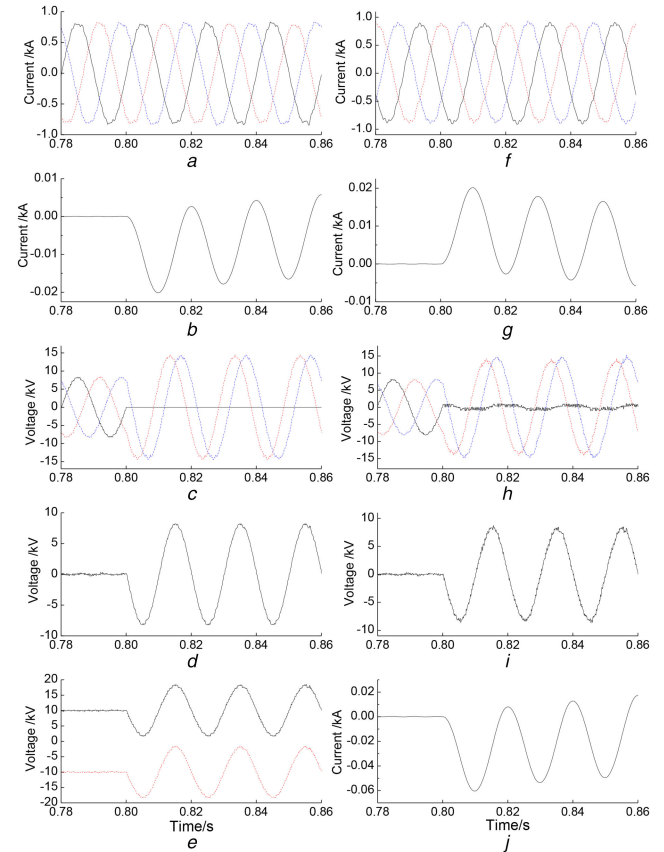


Fig. 3 Fault characteristics of supply area 1 and 2

(a) Response waveform of zero-sequence current in area 1, (b) Response waveform of AC voltage in area 1, (c) Response waveform of zero-sequence current in area 1, (d) Response waveform of zero-sequence voltage in area 1, (e) Response waveform of positive and negative DC voltages, (f) Response waveform of AC current in area 2, (g) Response waveform of zero-sequence current in area 2, (h) Response waveform of AC voltage in area 2, (i) Response waveform of zero-sequence voltage in area 2, (j) Response waveform of neutral current of area 2

### 4 Characteristic analysis of single-phase grounding fault

Fig. 4 gives an equivalent circuit diagram of MMC. The arm inductance is  $2L$ , and the equivalent arm resistance is  $2R$ . The three-phase voltage is represented by  $u_a$ ,  $u_b$  and  $u_c$ , respectively. The three-phase current is represented by  $i_a$ ,  $i_b$  and  $i_c$ , respectively. The pole-to-pole DC voltage and the DC current are represented by  $U_d$  and  $I_d$ , respectively. The positive and the negative DC voltages are represented by  $U_{dp}$  and  $U_{dn}$ , respectively, and the 'o' point is a virtual neutral point at the DC side. The upper and lower arm currents of phase  $j$  ( $j=a, b, c$ ) are expressed by  $i_{jp}$  and  $i_{jn}$ , respectively.  $u_{jp}$  and  $u_{jn}$  are the output voltage of the cascaded sub-

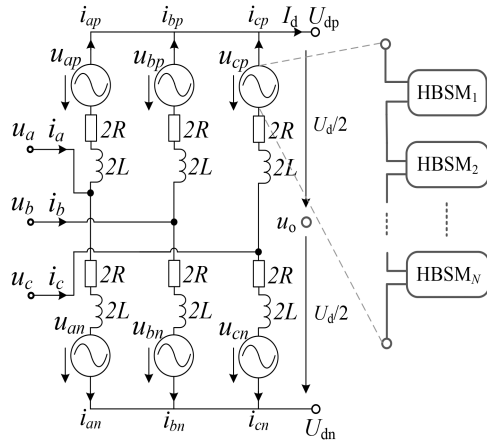


Fig. 4 MMC equivalent circuit diagram

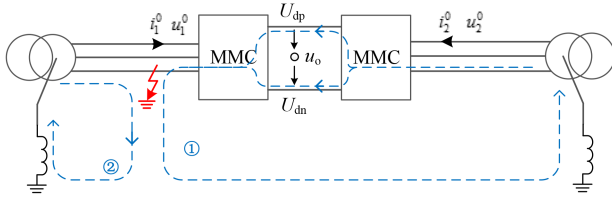


Fig. 5 Zero-sequence current path

module group of the upper and lower arm in phase  $j$ , and  $u_o$  is the DC neutral point to ground voltage.

Applying the Kirchhoff's voltage law to the upper and lower arms in phase  $j$ , we can obtain

$$u_j - 2L \frac{di_{jp}}{dt} - 2Ri_{jp} + u_{jp} = \frac{U_d}{2} + u_o = U_{dp} \quad (1)$$

$$u_j - 2L \frac{di_{jn}}{dt} - 2Ri_{jn} - u_{jn} = -\frac{U_d}{2} + u_o = U_{dn} \quad (2)$$

By adding (1) and (2), and then dividing two, a new equation is as follows

$$u_j - (e_j + u_o) = Ri_j + L \frac{di_j}{dt} \quad (3)$$

Where

$$e_j = \frac{u_{jn} - u_{jp}}{2} \quad (4)$$

Based on the symmetrical component theory, three independent subsystems (positive-sequence subsystem, negative-sequence subsystem and zero-sequence subsystem) can be obtained using the sequence component decomposition.

$$Ri_{abc}^+ + L \frac{di_{abc}^+}{dt} = u_{abc}^+ - e_{abc}^+ \quad (5)$$

$$Ri_{abc}^- + L \frac{di_{abc}^-}{dt} = u_{abc}^- - e_{abc}^- \quad (6)$$

$$Ri^0 + L \frac{di^0}{dt} = u^0 - e^0 - u_o \quad (7)$$

It can be seen from (5) and (6) that there is no element  $u_o$  in the positive and negative sequence subsystems, indicating that  $u_o$  is independent from the positive and negative sequence subsystems and is only determined by the zero-sequence subsystem. At present, the inner and outer loop control strategies under the positive and negative sequence subsystems have been very mature.

$e_{abc}^+$  and  $e_{abc}^-$  can be obtained simply by controlling the positive and negative sequence component. Since there is no zero-sequence control capability in the control loop, it can be derived that  $e^0 = 0$ . Equation (7) is suitable for H-MMCs in the supply area 1 and the supply area 2, so we can obtain

$$Ri_1^0 + L \frac{di_1^0}{dt} = u_1^0 - u_o \quad (8)$$

$$Ri_2^0 + L \frac{di_2^0}{dt} = u_2^0 - u_o \quad (9)$$

where the subscripts 1 and 2 represent area 1 and 2. From (8), it can be seen that the zero-sequence component caused by the fault in the area 1 leads to the fluctuation of  $u_o$ . According to (1) and (2), the positive and negative DC voltages ( $U_{dp}$  and  $U_{dn}$ ) are  $0.5U_d + u_o$  and  $u_o - 0.5U_d$ , respectively, so the fluctuation of  $u_o$  will lead to the offset of the positive and negative DC voltages, but the pole-to-pole DC voltage keeps constant. From (9), it can be seen that the AC side of the supply area 2 will be introduced in the zero-sequence voltage and zero-sequence current because of fluctuation of  $u_o$ . The zero-sequence current will flow through the neutral point of the supply area 2. Therefore, according to the analysis above, there are two paths for the zero-sequence current as shown in Fig. 5, after the single-phase grounding fault. The path ② is the circuit between the fault point and the neutral point of the area 1, similar to the conventional AC system grounding fault. In the path ①, the zero-sequence current passes through the neutral point of the area 2, the FMS and the fault point, which is different from the case with the connection transformer.

According to the circuit property shown in Fig. 5, following equations can be obtained.

$$u_2^0 = (Z_{l2} + 3Z_{g2})i_2^0 \quad (10)$$

$$u_s^0 - u_1^0 = Z_{l11}i_1^0 \quad (11)$$

$$u_s^0 = (Z_{l12} + 3Z_{g1})i_s^0 \quad (12)$$

where  $Z_{l2}$  is the zero-sequence equivalent impedance from the FMS to the substation in area 2,  $Z_{g2}$  is the neutral grounding reactance in area 2;  $Z_{l11}$  is the zero-sequence equivalent impedance from the FMS to the fault point,  $Z_{l12}$  the zero-sequence equivalent impedance from the fault point to the substation in area 1,  $Z_{g1}$  is the neutral grounding reactance in area 1.  $u_s^0$  is the zero-sequence voltage at the fault point,  $i_s^0$  is the zero-sequence current of the path ②.

According to the characteristics of positive, negative and zero sequence circuit under the single-phase grounding fault, the zero-sequence electrical quantities of these two supply areas can be calculated by combining (8)–(12).

## 5 Control scheme

Since the fault effect will transfer from the fault area to the non-fault area in the transformerless condition, proper measures should be taken to narrow the effect range. Here, a new protection and control scheme is proposed based on the feeder transformation. In the traditional distribution network, each feeder line has one breaker and several segment switches and loop switches. The breaker has large current interrupting capacity and is installed at the location of the substation outgoing line. The segment switch and loop switch always use the load switch which only has the rated current interrupting capacity. The fault isolation and power recovery are realised through the cooperation among the breaker and load switches.

After the integration of FMS as shown in Fig. 6, the feeder lines connected to FMS directly should adopt the feed automation, and the control right of the breaker S2 and load switches Q1–Q7 are transferred to FMS. Each segment of the feeder line connected to

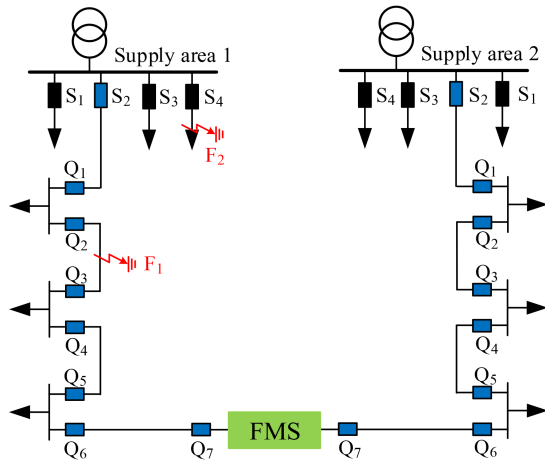


Fig. 6 Diagram of the distribution system with FMS

FMS should be covered with the optical fibre current differential protection.

If a single-phase grounding fault happens on the feeder line connected to the FMS (such as  $F_1$  in Fig. 6), the protection and control steps are as follows: (i) Fault location is finished according to the differential protection; (ii) The breaker  $S_2$  is opened; (iii) The H-MMC of FMS closed to the fault line switches to the passive control from the active control; (iv) The load switches closed to the fault segment are opened, and the fault is isolated; (v) The breaker  $S_2$  is closed if the fault is not in the segment between  $S_2$  and  $Q_1$ ; (vi) The distribution system recovers to the normal state. It can be seen that in this case, the load between the fault point and the breaker  $S_2$  will have a period of power outage, and the outage time is about tens of milliseconds during the opening of load switches and the closing of  $S_2$ . Other loads will not be affected.

If a single-phase grounding fault happens on the substation bus or other feeder lines (such as  $F_2$  in Fig. 6), the protection and control steps are as follows: (i) Fault location is finished according to the fault current direction; (ii) The breaker  $S_2$  is opened; (iii) The H-MMC of FMS closed to the fault line switches to the passive control from the active control; (iv) When the fault is isolated by the traditional method, the breaker  $S_2$  is closed and the MMC switches to the active control. Otherwise,  $S_2$  should not be closed and the MMC will always operate at the passive control state unless the fault is isolated. In this case, loads on the feeder line connected to the FMS will not have a power outage.

With the new scheme proposed above, the traditional protection and control devices and strategies of other feeder lines will not be

transformed, and only the feeder lines connected to FMS are updated, which is easy to be executed. Furthermore, the power supply reliability is guaranteed according to the analysis above. The key factor of the new scheme is the switching strategy between the active state and the passive state, which have been studied and designed in [9].

## 6 Conclusion

- (i) Without the transformer, the FMS loses the capability to isolate the zero-sequence component, and the zero-sequence voltage and zero-sequence current can transfer among the supply areas connected to FMS, which leads to the expansion of the fault range.
- (ii) The proposed protection and control strategy can inhibit the zero-sequence effect on the non-fault supply area effectively and quickly, and meanwhile, the power supply reliability is enhanced.

## 7 Acknowledgments

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