Application of Short-time Fourier Transform in Feeder Fault Detection of Flexible Multi-state Switch

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Abstract. Flexible multi-state switch (FMSS) is widely used in active distribution networks. However, the medium voltage distribution network that includes FMSS requires more accurate fault detection method. To solve this problem, the application of short-time Fourier transform (STFT) in the design of FMSS fault detection methods is studied. The data of power spectrum density in the STFT spectrogram is used to define the Fault Index, $\Lambda$. The $\Lambda$ can be used to accurately detect the fault type of FMSS in a relatively short time. In order to verify the effectiveness of this fault detection method, this paper builds a control structure for each port based on the FMSS topology and mathematical model. The FMSS model is simulated in MATLAB/Simulink, and the fault signal is analysed by STFT in MATLAB. The results show that the proposed fault detection method can accurately detect the fault type. The STFT parameters have a great influence on the fault detection result, which is studied in the parameters influence analysis.

1. Introduction

The flexible multi-state switch (FMSS) based on the voltage source converter is the development of the soft normally-open point (SNOP) concept proposed by Imperial College London in 2009[1-2]. Compared with the Tie Switch (TC) in the traditional distribution network, the FMSS has flexible power flow adjustment capabilities, and has great potential in improving the level of distributed power consumption, balancing the feeder load, and quickly restoring power supply [3]. Although FMSS has great advantages, in the medium voltage distribution network that includes FMSS, the network flow is more complicated, which requires further development of more reliable fault detection methods to protect the network.

The fault detection method of power grid that includes FMSS must meet the basic conditions of rapidity and reliability. The main signal processing methods currently used to design power system fault detection methods include wavelet transform (WT), short-time Fourier transform (STFT) and S transform (ST). In the reference [4], the author uses the S transform for real-time fault detection of high-voltage direct current transmission systems, and uses the frequency domain information of the fault signal to judge the fault condition. However, ST suffers from inherently poor frequency resolution,
particularly at the high frequencies. To solve this problem, reference [5] presents a technique (named STF) to enhance the frequency resolution through the use of the global Fourier spectrum. Reference [6] proposes a fault detection method that uses STFT to quantitatively analyse the high-frequency components in the fault current in a VSC-interfaced DC system, and compares its performance with WT. The result shows that STFT is faster than WT. Reference [7] designed a fault arc detection method based on wavelet transform and deep learning, which has a high accuracy of identifying low-voltage series fault arc.

In these signal processing methods, STFT can provide more accurate frequency information after setting a specific window size. So, this paper uses STFT to design FMSS fault detection method. A three-port FMSS model was built on the MATLAB/Simulink platform. After different kinds of faults occur on the feeder, current transient signals into the FMSS port are imported into MATLAB for STFT analysis, and the analysed fault transient spectrum data is used for fault detection research. Based on multiple tests and observations in different fault simulations, the Fault Index, \( \Lambda \) is defined by fault transient data to determine the type of fault in the feeder, so that the system can determine the type of fault within one period (0.02s) after the fault occurs. This is much lower than the detection time of general AC system fault-three periods (0.06s) \([8]\). In order to conduct a more accurate study, this article also conducted an analysis of the impact of STFT's important parameters (window length, etc.).

The rest of this article is arranged as follows: Section 2 briefly introduces the mathematical model of FMSS; Section 3 introduces STFT and proposed fault detection method; Section 4 describes the FMSS control strategy and simulation; Section 5 is the analysis of the influence of STFT parameters on the results; Section 6 is the summary and outlook of this article.

2. Mathematical model of FMSS

In order to verify the effectiveness of the proposed fault detection method, it is necessary to model and simulate the FMSS control system. FMSS is implemented based on fully controlled power electronic devices, and it can currently be implemented by back-to-back voltage source converters (VSC) or unified power flow controllers (UPFC) \([9]\). FMSS access to the distribution network topology is shown in figure 1.

![Figure 1. Distribution network access topology of FMSS](image)

The main circuit topology of the port converter is shown in figure 2. The three-port structure is symmetrical, and they are all composed of three-phase VSC, and the DC side is connected through a common capacitor.

![Figure 2. Port VSC main circuit topology](image)
According to the port VSC main circuit topology shown in figure 2, a three-phase grid voltage balance is set, if the output port adopts a single L filter, the mathematical model of FMSS under the synchronous rotating coordinate system is established after transformation [10].

\[
\begin{align*}
L \frac{di_{dk}}{dt} &= -Ri_{dk} + U_{dk} - s_{dk}U_{dk} + \omega Li_{qk} \\
L \frac{di_{qk}}{dt} &= -Ri_{qk} + U_{qk} - s_{qk}U_{qk} - \omega Li_{qk} \\
C \frac{dU_{dk}}{dt} &= \sum_{k=1,2,3} 3 \left( s_{dk}i_{qk} + s_{qk}i_{dk} \right)
\end{align*}
\]  

\(k=1,2,3\), the subscripts, \(k\) are all the same values; \(U_{dc}\) is the DC bus voltage of the FMSS; \(R\) and \(C\) are the equivalent resistance of the port VSC and the connection line loss and the FMSS DC side capacitor; \(\omega\) is the AC system voltage angular frequency; \(s_{dk}\) and \(s_{qk}\) are dq-axis components of the of the switch function of the port converter; \(i_{dk}\) and \(i_{qk}\) are dq-axis components of the AC output current of the port; \(U_{dk}\) and \(U_{qk}\) are dq-axis components of the AC system voltage of the port. It can be deduced that the active power and reactive power of each port of FMSS are:

\[
\begin{align*}
P_k &= \frac{3}{2} (U_{dk}i_{dk} + U_{qk}i_{qk}) \\
Q_k &= \frac{3}{2} (U_{qk}i_{dk} - U_{dk}i_{qk})
\end{align*}
\]

\(P_k\) and \(Q_k\) are the active and reactive power output of the port \(k\). Ignore the loss of FMSS and the connection line, the DC voltage is constant when the FMSS is working normally, according to the power conservation:

\[
\begin{align*}
P_k &= U_{dk}i_{dk} \\
\sum_{k=1,2,3} P_k &= 0
\end{align*}
\]

Where \(i_{dk}\) is the current flowing from the \(k\) port VSC into the DC side.

3. STFT and proposed fault detection method

Taking STFT as the main signal processing tool of the proposed method, using the spectrogram data obtained through STFT transformation for fault detection, the frequency change and harmonic frequency range of the fault signal can also be seen through the spectrogram.

3.1 Short-time Fourier Transform

STFT is a classic time-frequency analysis method, and its result has a direct correspondence with the signal spectrum. Compared with the traditional Fourier transform suitable for processing stable signals, STFT has a greater advantage in processing transient signals. Its working principle is to add a short-time window function to the signal to be analysed. These window functions include rectangular window, Gaussian window, Hanning window, Hamming window, etc. The set window function will move along the time domain of the signal according to the number of hops. The short window will take out the slices of the signal near each time, and perform Fourier transform on them respectively, and then obtain the frequency spectrum (local frequency spectrum) near each time [11].

Suppose the window function is \(h(t)\) and the signal to be analysed is \(s(t)\), then the STFT transformation of this signal is defined as:

\[
STFT(\omega,t) = \frac{1}{2\pi} \int e^{i\omega\tau} s(\tau) h(\tau - t) d\tau
\]

(4)

The type and length of the window function will affect the results of the STFT, which is specifically manifested in the time resolution and frequency resolution of the spectrogram. When the window length is larger, the frequency resolution of the analysis result is better, while the time resolution will be
correspondingly worse. This is also one of the shortcomings of STFT, that is, it cannot take into account both frequency and time resolution requirements. On the basis of multiple experiments, a Hamming window with a length of 21,000 samples is selected, and the number of repeated points between the windows is set to 1,000 samples to improve the time domain analysis capability. Figure 3 is the frequency spectrum of the port current of the FMSS in normal operation. It can be seen that the signal frequency is stable at 50Hz at this time, and the harmonic content is very low.

Figure 3. Spectrogram of FMSS port current under normal working conditions

3.2 Proposed fault detection method

When the window type and window length are determined, the FMSS model is simulated for multiple different faults, and then STFT is used to process the fault current of the FMSS port. The results show that in different faults, the amplitude and frequency domain characteristics of the FMSS port current are quite different, which causes the maximum power spectral density (Power/Frequency, dB/Hz) detected by STFT to change greatly compared with the FMSS without fault. Therefore, a Fault Index, \( \Lambda \) is defined based on the maximum power spectral density detected by STFT, and the fault type can be identified by the \( \Lambda \).

![Flowchart of fault detection](image)

Figure 4. Flowchart of fault detection
The $\Lambda$ is defined as follows:

$$\Lambda = \frac{P_{f_{\text{max}} \cdot \text{fault}}}{P_{f_{\text{max}} \cdot \text{normal}}}$$  \hspace{1cm} (5)$$

Where $P_{f_{\text{max}} \cdot \text{fault}}$ and $P_{f_{\text{max}} \cdot \text{normal}}$ are the maximum power spectral density obtained by STFT analysis of the port fault current and normal current. When the FMSS model is operating normally and stably, the amplitude and frequency of the FMSS port current will not change, and the sampling frequency, window length, and repetition rate between windows will not change after the system is determined. Therefore, when the system is running normally, $P_{f_{\text{max}} \cdot \text{normal}}$ also remains unchanged, and $P_{f_{\text{max}} \cdot \text{normal}} = 1.191$, this can also be seen in figure 1. Based on multiple tests and observations in different fault simulations, when a three-phase ground fault (PPP4G) occurs, $P_{f_{\text{max}} \cdot \text{fault}}$ is small, and the $\Lambda$ is close to 0; when a single-phase-to-ground (NP2G) fault occurs, $P_{f_{\text{max}} \cdot \text{fault}}$ is large, and the $\Lambda$ rises sharply; and when a phase-to-phase short-circuit fault (P2P) occurs, the $\Lambda$ is at between the two. Considering the error value of 0.05, the fault type of FMSS feeder can be judged according to the following conditions:

- $0 < \Lambda < 0.95$ range1
- $0.95 < \Lambda < 1.05$ range2
- $1.05 < \Lambda < 1.55$ range3
- $\Lambda > 1.55$ range4

$$\begin{cases} 
0 < \Lambda < 0.95 & \text{range1} \\
0.95 < \Lambda < 1.05 & \text{range2} \\
1.05 < \Lambda < 1.55 & \text{range3} \\
\Lambda > 1.55 & \text{range4}
\end{cases}$$  \hspace{1cm} (6)$$

Based on the above content, the flowchart of fault detection can be designed, as shown in figure 4.

## 4. FMSS control strategy and simulation

### 4.1 FMSS control strategy

In this paper, a double closed-loop control strategy is used to control the VSC, and according to the actual operating conditions of FMSS, an improved control structure combining PI controller and steady-state inverse model is designed for each mode in figure 5\[10\].

![Control structure of FMSS port](image)

In figure 5, $i_d$ and $i_q$ is estimated current value obtained from the steady-state inverse model; $\Delta i_d$ and $\Delta i_q$ are current correction amounts output by PI controller; $Q$ and $Q_{\text{ref}}$ is port output reactive power and reactive power reference value; $U_d$ and $U_q$ are $dq$-axis components of the AC system voltage of the port.

For the port of $U_{dc}$-$Q$, it needs to maintain the power balance of the entire system, at this time $X_1$ and $X_{1\text{ref}}$ represent $U_{dc}$ and $U_{dc\text{ref}}$, respectively, that is, DC bus voltage of the FMSS and its reference value. $X_2$ represents $P_{\text{ref}}$, is the required output active power of the $U_{dc}$-$Q$ port.

For the port of P-$Q$, $X_1$ and $X_{1\text{ref}}$ represent $P$ and $P_{\text{ref}}, X_2$ represents $P_{\text{ref}}$, too. $P$ and $P_{\text{ref}}$ is port output active power and reference value.

### 4.2 Simulation

In order to verify the effectiveness of the fault detection method proposed in this paper, an FMSS test model was built on the MATLAB/Simulink platform, and three fault simulations (PPP4G, P2P and NP2G) were performed on the feeder 2. After the fault occurs, detect A phase current on the feeder 2 of FMSS port and perform STFT analysis. Port 1 of the test system adopts $U_{dc}$-$Q$ control mode, and ports...
2 and 3 adopt P-Q control mode. The parameters and initial conditions of the test system are given in reference [10], and other configurations of the system are given in Table 1.

| Power/Frequency Threshold | Sampling Frequency | Window Size | Hop Size |
|---------------------------|--------------------|-------------|----------|
| 1.2 dB/Hz                 | 1000 kHz           | 21000 Samples | 1000 Samples |

4.2.1 Fault 1
In the first fault situation, a three-phase-to-ground fault is applied to the FMSS after 0.2s normal operation on feeder 2. After the fault, the current on the AC side of FMSS port on feeder 2 rapidly drops to 0, and the phase A current waveform, \( i_{\text{fault1}} \), is shown in figure 6. Input the fault current to the MATLAB workplace for STFT analysis, and the resulting spectrum diagram is shown in figure 7. It can be seen from the figure that the frequency of the waveform drops rapidly to 0 after the fault, and the corresponding power spectral density also drops sharply.

4.2.2 Fault 2
In the second fault, a two-phase short-circuit fault between phase A and B is applied to the FMSS. The fault still occurs on the power supply side of feeder 2 after 0.2s. The initial system condition settings remain unchanged. After the fault, the current of phase A of the FMSS port on feeder 2, \( i_{\text{fault2}} \), is no longer a sine wave, and the fault current waveform and the frequency spectrum obtained after STFT analysis are shown in figure 8 and figure 9.
4.2.3 Fault 3

Fault 3 is a grounding fault of phase A on feeder 2 of the FMSS that occurred 0.2s after normal operation. The initial operating conditions of the system remain unchanged. Figure 10 shows the A-phase current waveform of port on feeder 2 after fault, $i_{afault3}$. And figure 11 shows the result of STFT analysis of this current.

According to (5), the $\Lambda$ under three conditions can be calculated. The maximum power spectral density and other data after the occurrence of the three faults are given in Table 2. According to the simulation results in the table, the fault type judgment conditions given by (6) and the flowchart in figure 2, the accuracy of the fault detection method proposed can be verified.

| Fault | $P_{f_{max\ fault}}$, dB/Hz | $P_{f_{max\ normal}}$, dB/Hz | $\Lambda$ | Range | Fault type |
|-------|-------------------------------|-------------------------------|----------|-------|------------|
| Fault 1 | $8.525 \times 10^{-5}$ | 1.191 | $7.159 \times 10^{-5}$ | Range 1 | PPP4G |
| Fault 2 | 1.347 | 1.191 | 1.131 | Range 3 | P2P |
| Fault 3 | 2.288 | 1.191 | 1.921 | Range 4 | NP2G |

5. Influence of STFT parameters

STFT analysis results are affected by its parameters, which include the type of window function, window length, and the number of repeated points between the windows. After many tests, it was found that the STFT analysis results of different window function types had little difference, so the Hamming window
was finally selected. However, the window length and the inter-window repetition rate have a greater impact on the fault detection accuracy. The following part analyses and compares the fault spectrograms with window lengths of 21000 and 10000 samples and the number of repeated points between the windows of 1000 and 5000 samples.

5.1 Window length
The window length is one of the most important parameters of STFT, and different window lengths will directly affect the time resolution and frequency resolution of the spectrogram. The larger the window length, the better the frequency resolution and the lower the accuracy of the time resolution. Figure 12 shows the spectrum analysis results of \( i_{\text{afault3}} \) in fault 3 when the window length is 21000 and 10000 respectively. It can be seen that a window of 21,000 samples can express the frequency more clearly, and when the window length is 10,000 samples, the accuracy of the frequency resolution is lower. However, if the window length is selected too large, the time resolution will also deteriorate. Based on the sampling frequency selected in this article and the required time-frequency resolution, the final selected window length is 21000 samples.

![Figure 12. Spectrum diagram of \( i_{\text{afault3}} \) with different window length: (a) 21000 samples; (b) 10000 samples.](image)

5.2 Repeated points between windows
The repeated points between windows has an equally important impact on the analysis results of STFT. It is specifically manifested in its impact on the time resolution of the spectrogram. Because the results of STFT analysis in this article will be used for fault detection, and the time resolution has a great influence on fault detection, that is, the fault must be detected as soon as it occurs. Figure 13 compares the STFT diagrams of \( i_{\text{afault3}} \) when the window length is 21000 samples and the repeated points between windows is 1000 and 5000 samples. It can be seen from the figure that the time-frequency resolution is better when the inter-window repeated points is 1000 compared to 5000.

In summary, this paper finally selected a Hamming window with the length of 21,000 samples, and set the repeated points between windows to 1,000 samples.
6. Conclusion
This paper uses STFT spectrogram data for FMSS fault detection: after STFT analysis of fault current, data such as power spectral density is obtained, if the detected power spectral density exceeds the set threshold, it is determined that a fault has occurred, and then the type of fault that has occurred can be judged by calculating a predefined Fault Index, $\Lambda$. Different fault indexes in different intervals correspond to different fault types. So, the type of fault can be determined within one period (0.02s) after the fault occurs by this method. In order to verify the effectiveness of the fault detection method, this paper designs an effective control structure for each port and the FMSS model is simulated in MATLAB/Simulink. STFT parameters have a great influence on the time-frequency resolution and the size of the power spectral density, the STFT parameters influence analysis shows how the parameters affect the accuracy of the proposed fault detection method. The next step is to study the application of this detection method to the FMSS fault protection algorithm and determine the exact location of the fault, so that FMSS can quickly respond after detecting a fault, and then switch the port mode and remove the fault.

Acknowledgments
This work was supported by National Key R&D Program of China (2017YFB0903100) and Science and Technology Projects of State Grid Corporation of China (521104170043).

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