

ORIGINAL RESEARCH

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# Research on fault diagnosis for MMC-HVDC Systems



Zhiqing Yao<sup>1\*</sup>, Qun Zhang<sup>2</sup>, Peng Chen<sup>2</sup> and Qian Zhao<sup>2</sup>

## Abstract

**Introduction:** With the development of flexible HVDC technology, the fault diagnosis of MMC-HVDC becomes a new research direction.

Based on the fault diagnosis theory, this paper proposes a robust fault diagnosis method to study the fault diagnosis problem of MMC-HVDC systems.

**Methods:** By optimizing the gain matrix in the fault observer, fault detection with good sensitivity and robustness to disturbance is achieved. In the MMC-HVDC system, because of the inherently uncertain system and the presence of various random disturbances, the study of robust fault diagnosis method is particularly important.

**Results:** Simulation studies during various AC faults have been carried out based on a 61-level MMC-HVDC mathematical model. The results validate the feasibility and effectiveness of the proposed fault diagnosis method.

**Conclusions:** So this fault diagnosis method can be further applied to the actual project, to quickly achieve system fault diagnosis and accurately complete fault identification.

**Keywords:** Fault diagnosis, MMC-HVDC, Robust, State observer, Residual state equation

## Introduction

In recent years, due to the increased size and complexity of control systems, fault diagnosis becomes particularly important, especially in power systems [1]. For instance, if line faults are not quickly detected and isolated, they can cause system failure or even lead to disastrous consequences [2]. Currently, there are many fault diagnosis methods, such as the diagnostic filter method, parameter identification method, expert system, artificial neural network etc. [3–5]. Although these methods can effectively detect failures in the system, they cannot precisely estimate these fault signals.

This paper proposes a fault diagnosis method based on full dimension state observer for flexible HVDC system. State estimation is carried out using the mathematical model of a three-phase 61-level modular multilevel converter (MMC) based HVDC (MMC-HVDC) system and the full dimension state observer. Residual state equation is established and is combined with the system output and system phasor. By optimizing the gain matrix in fault observer, the robustness of the fault detection is

investigated. In the MMC-HVDC system, because the system is inherently uncertain and there are various random disturbances, the study of robust fault diagnosis method is particularly important.

## Methods

### Model of MMC-HVDC

A three-phase MMC topology is shown in Fig. 1 [6–9]. According to KCL, the three-phase current can be expressed as

$$\begin{cases} i_a = i_{pa} + i_{na} \\ i_b = i_{pb} + i_{nb} \\ i_c = i_{pc} + i_{nc} \end{cases} \quad (1)$$

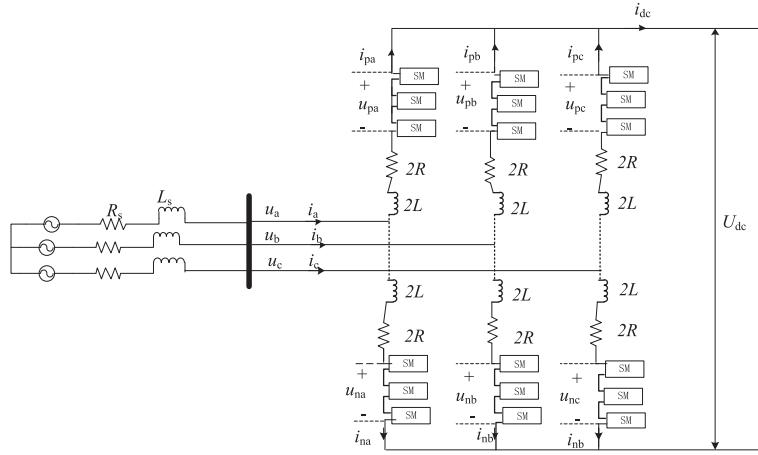
For three single-phase units, applying KVL to the upper and lower arms yields:

$$\begin{cases} u_a - \left( \frac{U_{dc}}{2} - u_{pa} \right) = 2L \frac{di_{pa}}{dt} + 2Ri_{pa} \\ u_b - \left( \frac{U_{dc}}{2} - u_{pb} \right) = 2L \frac{di_{pb}}{dt} + 2Ri_{pb} \\ u_c - \left( \frac{U_{dc}}{2} - u_{pc} \right) = 2L \frac{di_{pc}}{dt} + 2Ri_{pc} \end{cases} \quad (2)$$

\* Correspondence: zhiqingy@dlwg.net

<sup>1</sup>Xuchang KETOP Electrical Research Institute, Xuchang, China

Full list of author information is available at the end of the article



**Fig. 1** Three phase MMC topology

$$\begin{cases} u_a - \left( u_{na} - \frac{U_{dc}}{2} \right) = 2L \frac{di_{na}}{dt} + 2Ri_{na} \\ u_b - \left( u_{nb} - \frac{U_{dc}}{2} \right) = 2L \frac{di_{nb}}{dt} + 2Ri_{nb} \\ u_c - \left( u_{nc} - \frac{U_{dc}}{2} \right) = 2L \frac{di_{nc}}{dt} + 2Ri_{nc} \end{cases} \quad (3)$$

In the above equations,  $2L$  and  $2R$  denote the equivalent arm inductance and resistance, respectively. Adding Eqs. (2) and (3) leads

$$\begin{cases} u_a - (u_{na} - u_{pa})/2 = L \frac{di_a}{dt} + Ri_a \\ u_b - (u_{nb} - u_{pb})/2 = L \frac{di_b}{dt} + Ri_b \\ u_c - (u_{nc} - u_{pc})/2 = L \frac{di_c}{dt} + Ri_c \end{cases} \quad (4)$$

According to Eq. (4), the time domain mathematic model of a MMC in abc coordinate is given by [10, 11].

$$\begin{cases} \frac{di_a(t)}{dt} = -\frac{R}{L}i_a(t) + \frac{1}{L}[u_a(t) - (u_{na}(t) - u_{pa}(t))/2] \\ \frac{di_b(t)}{dt} = -\frac{R}{L}i_b(t) + \frac{1}{L}[u_b(t) - (u_{nb}(t) - u_{pb}(t))/2] \\ \frac{di_c(t)}{dt} = -\frac{R}{L}i_c(t) + \frac{1}{L}[u_c(t) - (u_{nc}(t) - u_{pc}(t))/2] \end{cases} \quad (5)$$

Written Eq. (5) in phasor form yields

$$\begin{aligned} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} &= \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ \begin{bmatrix} -\frac{1}{2L} & \frac{1}{2L} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{2L} & \frac{1}{2L} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{2L} & \frac{1}{2L} \end{bmatrix} \begin{bmatrix} u_{na} \\ u_{pa} \\ u_{nb} \\ u_{pb} \\ u_{nc} \\ u_{pc} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \end{aligned} \quad (6)$$

Considering the uncertainty, external disturbances and system faults, the Eq. (6) can be written as follows

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{h}(t) + \Delta(t) + \mathbf{B}_f\mathbf{f}(t) \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{M}(t) \end{cases} \quad (7)$$

$$\begin{aligned} \text{where } \mathbf{x}(t) &= \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \mathbf{u}(t) = \begin{bmatrix} u_{na} \\ u_{pa} \\ u_{nb} \\ u_{pb} \\ u_{nc} \\ u_{pc} \end{bmatrix}, \mathbf{A} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix}, \\ \mathbf{B} &= \begin{bmatrix} -\frac{1}{2L} & \frac{1}{2L} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{2L} & \frac{1}{2L} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{2L} & \frac{1}{2L} \end{bmatrix}, \mathbf{h}(t) = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}. \end{aligned}$$

In Eq. (7),  $\Delta(t)$  represents uncertainty and external disturbances generated during the actual modeling process.  $\mathbf{f}(t)$  represents the system faults which are required to

detect and identify.  $\mathbf{M}(t)$  is measurement noise introduced by the measurement system.  $\mathbf{B}_f$ ,  $\mathbf{C}$  and  $\mathbf{D}$  are known matrices with appropriate dimensions.  $\mathbf{y}(t)$  is the system output. If  $\mathbf{\Omega}(t)$  is used to represent  $\Delta(t) + \mathbf{h}(t)$ , Eq. (7) can be written as follows.

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{\Omega}(t) + \mathbf{B}_f\mathbf{f}(t) \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{M}(t) \end{cases} \quad (8)$$

For further analysis, the following assumptions are made:

- 1) Uncertainties in the system are norm-bounded, that is  $\|\Delta(t)\| \leq V_\Delta$ .
- 2) System matrix pair  $(\mathbf{A}, \mathbf{C})$  is observable.
- 3) Uncertainties in the system meet the condition  $\|\mathbf{\Omega}(t)\| \leq \gamma\|\mathbf{x}(t)\| \leq V_\Omega$ .
- 4) The  $\mathbf{M}(t)$  in the system is norm-bounded, that is  $\|\mathbf{M}(t)\| \leq V_M$ .
- 5) The initial state of the system is zero.

#### Design of full dimension state observer

Fault diagnosis is carried out by full dimension state observer based on the state equation of flexible HVDC system [12–14]. It can be seen from Eq. (8) that  $\mathbf{\Omega}(t)$  contains the system uncertainties and external disturbance, and the grid voltage  $u_a$ ,  $u_b$ ,  $u_c$ , which can be regarded as unknown nonlinear perturbation term.

A state observer is established according to Eq. (8):

$$\begin{cases} \dot{\hat{\mathbf{x}}}(t) = \mathbf{A}\hat{\mathbf{x}}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{H}(\mathbf{y}(t) - \hat{\mathbf{y}}(t))\hat{\mathbf{y}}(t) = \mathbf{C}\hat{\mathbf{x}}(t) \end{cases} \quad (9)$$

In Eq. (9),  $\mathbf{H}$  is a gain matrix to be designed. According to Eqs. (8) and (9), system residual state equation is given by:

$$\begin{cases} \dot{\mathbf{x}}(t) - \dot{\hat{\mathbf{x}}}(t) = (\mathbf{A} - \mathbf{H}\mathbf{C})(\mathbf{x}(t) - \hat{\mathbf{x}}(t)) + \mathbf{\Omega}(t) + \mathbf{B}_f\mathbf{f}(t) \\ -\mathbf{H}\mathbf{D}\mathbf{M}(t)\mathbf{y}(t) - \hat{\mathbf{y}}(t) = \mathbf{C}(\mathbf{x}(t) - \hat{\mathbf{x}}(t)) + \mathbf{D}\mathbf{M}(t) \end{cases} \quad (10)$$

If  $\mathbf{e}(t) = \mathbf{x}(t) - \hat{\mathbf{x}}(t)$  and  $\mathbf{r}(t) = \mathbf{y}(t) - \hat{\mathbf{y}}(t)$ , Eq. (10) can be written as follows:

$$\begin{cases} \dot{\mathbf{e}}(t) = (\mathbf{A} - \mathbf{H}\mathbf{C})\mathbf{e}(t) + \mathbf{\Omega}(t) + \mathbf{B}_f\mathbf{f}(t) - \mathbf{H}\mathbf{D}\mathbf{M}(t) \\ \mathbf{r}(t) = \mathbf{C}\mathbf{e}(t) + \mathbf{D}\mathbf{M}(t) \end{cases} \quad (11)$$

In the design of the full dimension state observer, the impact of the fault and external disturbance or uncertainties on the residual should be considered. The transfer function from system uncertainties and external disturbance to residual  $\mathbf{r}(t)$  is presented by  $\mathbf{T}_{rd}$  whereas  $\mathbf{T}_{rf}$  presents the transfer function from system fault to residual  $\mathbf{r}(t)$ . If the value of  $\|\mathbf{T}_{rd}\|$  is small enough and

the value of  $\|\mathbf{T}_{rf}\|$  is big enough in the design, the designed observer will be robust. Therefore, the following performance index is used to design the fault diagnosis observer:

$$J = \frac{\|\mathbf{T}_{rf}\|}{\|\mathbf{T}_{rd}\|} \quad (12)$$

In practical applications, the above performance index can be equivalent to the following equation:

$$\|\mathbf{r}(t)\|_\infty \leq \beta\|\mathbf{d}(t)\|_\infty, \|\mathbf{r}(t)\|_- \geq \eta\|\mathbf{f}(t)\|_- \quad (13)$$

Equation (13) can be solved by using multi-objective optimization methods and thus the robust control theory will be used to solve the performance optimization problem proposed by Eq. (13).

**Theorem 1** The system represented by Eq. (8) satisfies the assumptions (1)–(5). Optimization index  $\beta$  is given and satisfies the condition  $\mathbf{D}^T\mathbf{D} - \beta^2\mathbf{I} < 0$ . In case of no fault in the system, if there are a positive definite symmetric matrix  $\mathbf{R}$  and a constant factor  $\varepsilon_1 > 0$  meeting the following linear matrix inequality:

$$\begin{bmatrix} \mathbf{R}(\mathbf{A} - \mathbf{H}\mathbf{C}) + (\mathbf{A} - \mathbf{H}\mathbf{C})^T\mathbf{R} + \varepsilon_1^{-1}\mathbf{R}^T\mathbf{R} + \mathbf{C}^T\mathbf{C} & 0 & \mathbf{C}^T\mathbf{D} - \mathbf{R}\mathbf{H}\mathbf{D} \\ 0 & \varepsilon_1\gamma^2\mathbf{I} & 0 \\ \mathbf{D}^T\mathbf{C} - (\mathbf{R}\mathbf{H}\mathbf{D})^T & 0 & \mathbf{D}^T\mathbf{D} - \beta^2\mathbf{I} \end{bmatrix} \quad (14)$$

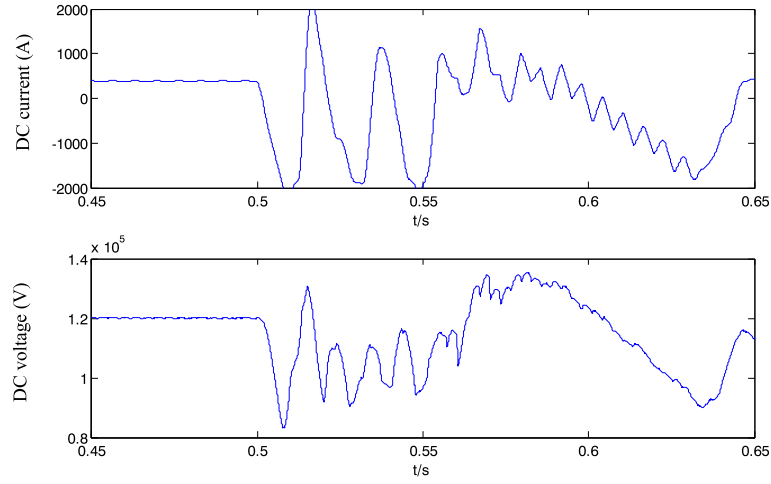
the residual system (11) is asymptotically stable and meets  $\|\mathbf{r}(t)\|_\infty \leq \beta\|\mathbf{d}(t)\|_\infty$ .

**Theorem 2** The system represented by Eq. (8) satisfies the assumptions (1)–(5). Optimization index  $\eta$  is given and satisfies the condition  $\mathbf{D}^T\mathbf{D} - \eta^2\mathbf{I} < 0$ . In case of no fault in the system, if there are a positive definite symmetric matrix  $\mathbf{T}$  and a constant factor  $\eta_1 > 0$  meeting the following linear matrix inequality:

$$\begin{bmatrix} \mathbf{R}(\mathbf{A} - \mathbf{H}\mathbf{C}) + (\mathbf{A} - \mathbf{H}\mathbf{C})^T\mathbf{R} + \eta_1^{-1}\mathbf{R}^T\mathbf{R} + \mathbf{C}^T\mathbf{C} & 0 & -\mathbf{C}^T\mathbf{D} + \mathbf{R}\mathbf{H}\mathbf{D} \\ 0 & \eta_1\gamma^2\mathbf{I} & 0 \\ -\mathbf{D}^T\mathbf{C} + (\mathbf{R}\mathbf{H}\mathbf{D})^T & 0 & \eta^2\mathbf{I} - \mathbf{D}^T\mathbf{D} \end{bmatrix} \quad (15)$$

The residual system (11) is asymptotically stable and meets  $\|\mathbf{r}(t)\|_- \geq \eta\|\mathbf{f}(t)\|_-$ .

**Theorem 3** The system represented by Eq. (8) satisfies the assumptions (1)–(5). Optimization index  $\beta > 0$ ,  $\eta > 0$  are given. If there are positive definite symmetric matrix  $\mathbf{R}$ ,  $\mathbf{T}$ ,  $\mathbf{H}$ , constant factor  $\varepsilon_1 < 0$  and  $\eta_1 > 0$  meeting the following linear matrix inequality:



**Fig. 2** Phase-A to ground fault

$$\begin{bmatrix} \mathbf{R}(\mathbf{A}-\mathbf{H}\mathbf{C}) + (\mathbf{A}-\mathbf{H}\mathbf{C})^T \mathbf{R} + \varepsilon_1^{-1} \mathbf{R}^T \mathbf{R} + \mathbf{C}^T \mathbf{C} & 0 & \mathbf{C}^T \mathbf{D} - \mathbf{R} \mathbf{H} \mathbf{D} \\ 0 & \varepsilon_1 \gamma^2 \mathbf{I} & 0 \\ \mathbf{D}^T \mathbf{C} - (\mathbf{R} \mathbf{H} \mathbf{D})^T & 0 & \mathbf{D}^T \mathbf{D} - \beta^2 \mathbf{I} \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} \mathbf{R}(\mathbf{A}-\mathbf{H}\mathbf{C}) + (\mathbf{A}-\mathbf{H}\mathbf{C})^T \mathbf{R} + \eta_1^{-1} \mathbf{R}^T \mathbf{R} + \mathbf{C}^T \mathbf{C} & 0 & -\mathbf{C}^T \mathbf{D} + \mathbf{R} \mathbf{H} \mathbf{D} \\ 0 & \eta_1 \gamma^2 \mathbf{I} & 0 \\ -\mathbf{D}^T \mathbf{C} + (\mathbf{R} \mathbf{H} \mathbf{D})^T & 0 & \eta^2 \mathbf{I} - \mathbf{D}^T \mathbf{D} \end{bmatrix} \quad (17)$$

The residual system (11) is asymptotically stable and meets  $\|r(t)\|_\infty \leq \beta \|d(t)\|_\infty$  and  $\|r(t)\|_- \geq \eta \|f(t)\|_-$ .

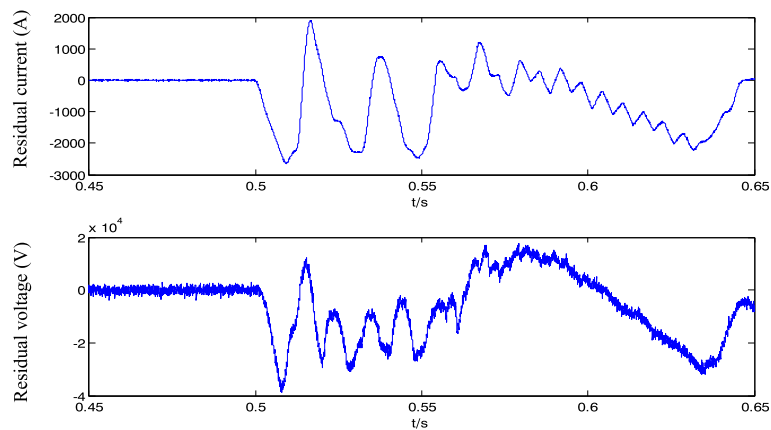
The gain matrix  $\mathbf{H}$  of the full dimension state observer can be obtained from Theorem 3. The design process of gain matrix  $\mathbf{H}$  takes into account the impact of system disturbances and uncertainties on the residual, and the sensitivity of the residual for faults.

#### Determination of fault detection threshold

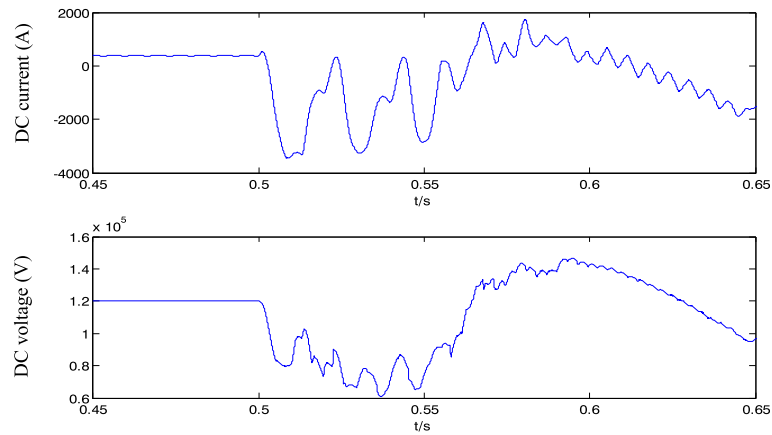
When disturbances or uncertainties exist in the system, a fault detection threshold method is usually used to determine whether the system has a fault [15–17]. This section provides fault detection thresholds calculated according to the definition of norm.

**Theorem 4** The system represented by Eq. (8) satisfies the assumptions (1)–(5). If the residual system (11) meets  $\|r(t)\| > (aV_\Omega + bV_M)(t - t_0) + cV_M$ , then system fault is detected, where  $a = \sup_{t \in [t_0, t]} \|\mathbf{C}\Psi(t, s)\|$ ,  $b = \sup_{t \in [t_0, t]} \|\mathbf{C}\Psi(t, s)\mathbf{H}\mathbf{D}\|$ ,  $c = \sup_{t \in [t_0, t]} \|\mathbf{D}\|$ .

**Proof** According to the residual state Eq. (11) the following two equations can be derived:



**Fig. 3** Residual error curve during phase-A to ground fault



**Fig. 4** Phase-AB to ground fault

$$\mathbf{e}(t) = \Psi(t, t_0)\mathbf{e}(t_0) + \int_{t_0}^t \Psi(t, s)[\mathbf{\Omega}(t) + \mathbf{B}_f \mathbf{f}(t) - \mathbf{HDM}(t)]ds \quad (18)$$

$$\mathbf{r}(t) = \mathbf{C} \left\{ \Psi(t, t_0)\mathbf{e}(t_0) + \int_{t_0}^t \Psi(t, s)[\mathbf{\Omega}(t) + \mathbf{B}_f \mathbf{f}(t) - \mathbf{HDM}(t)]ds \right\} + \mathbf{DM}(t) \quad (19)$$

According to assumption (5),  $\mathbf{e}(t_0) = 0$ . Thus

$$\mathbf{r}(t) = \int_{t_0}^t \mathbf{C}\Psi(t, s)[\mathbf{\Omega}(t) + \mathbf{B}_f \mathbf{f}(t) - \mathbf{HDM}(t)]ds + \mathbf{DM}(t) \quad (20)$$

Equation (21) can be obtained by seeking norm in both sides as

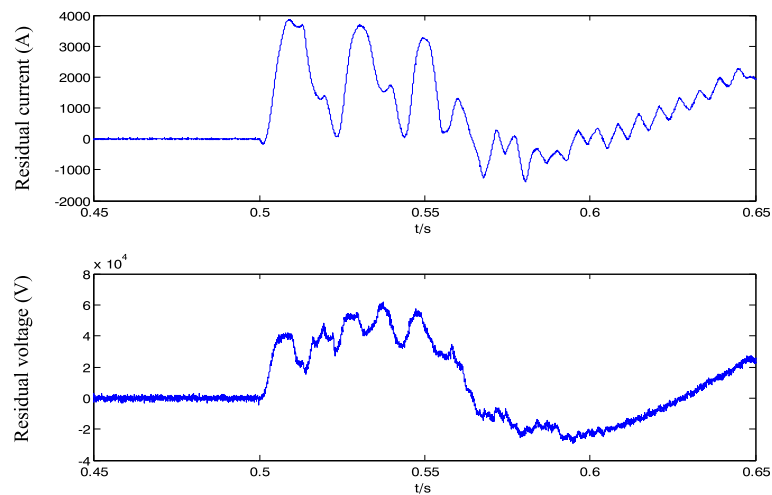
$$\|\mathbf{r}(t)\| \leq \int_{t_0}^t \|\mathbf{C}\Psi(t, s)\mathbf{\Omega}(t)\|ds + \int_{t_0}^t \|\mathbf{C}\Psi(t, s)\mathbf{B}_f \mathbf{f}(t)\|ds + \int_{t_0}^t \|\mathbf{C}\Psi(t, s)\mathbf{HDM}(t)\|ds + \|\mathbf{DM}(t)\| \quad (21)$$

where  $a = \sup_{t \in [t_0, t]} \|\mathbf{C}\Psi(t, s)\|$ ,  $b = \sup_{t \in [t_0, t]} \|\mathbf{C}\Psi(t, s)\mathbf{H}\mathbf{D}\|$ ,  $c = \sup_{t \in [t_0, t]} \|\mathbf{D}\|$

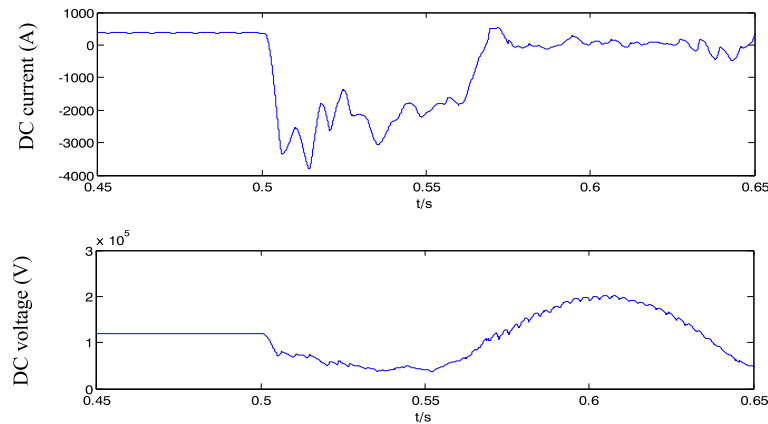
According to assumptions (1)-(4), Eq. (22) is obtained as

$$\|\mathbf{r}(t)\| \leq \int_{t_0}^t a \|\mathbf{\Omega}(t)\|ds + \int_{t_0}^t b \|\mathbf{M}(t)\|ds + \|\mathbf{DM}(t)\| \quad (22)$$

Equation (22) can be simplified as



**Fig. 5** Residual error curve during phase-AB to ground fault



**Fig. 6** Three phase to ground fault

$$\begin{aligned}
 \|\mathbf{r}(t)\| &\leq \int_{t_0}^t a\mathbf{V}_{\Omega}ds + \int_{t_0}^t b\mathbf{V}_Mds + c\mathbf{V}_M \\
 &= a\mathbf{V}_{\Omega}(t-t_0) + b\mathbf{V}_M(t-t_0) + c\mathbf{V}_M \\
 &= (a\mathbf{V}_{\Omega} + b\mathbf{V}_M)(t-t_0) + c\mathbf{V}_M
 \end{aligned} \quad (23)$$

Proof is done.

## Results

### Simulation results

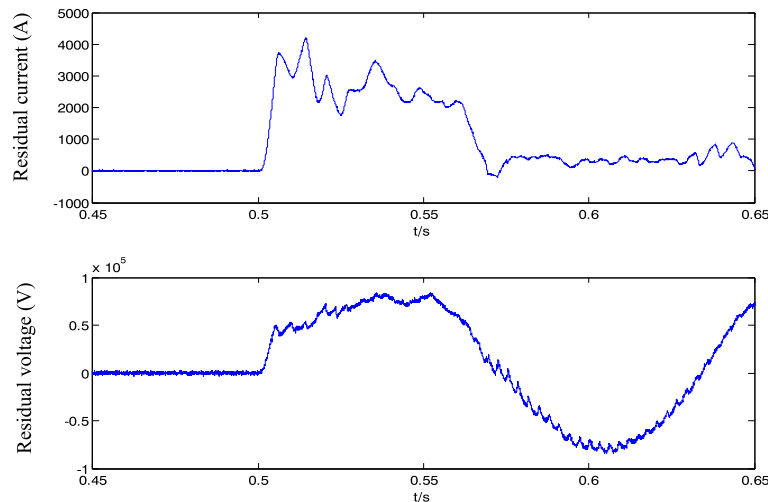
According to the MMC-HVDC system state Eq. (7), common types of fault, e.g. phase A to ground fault, phase-AB to ground fault, three phase to ground fault are simulated based on the 61-level MMC-HVDC system using Matlab/Simulink and RT-LAB.

The rated DC voltage of the system is 120 kV and the rated active power is 50 MW. The rectifier controls active power control and the inverter controls the DC voltage. AC fault is simulated during 0.5 to 0.55 s. The

simulation output voltage and current waveforms are shown in Figs. 2, 3, 4, 5, 6 and 7.

### Phase-A to ground fault

Figure 2 shows the DC bus voltage and current waveform when the phase-A to ground fault occurs in the rectifier side. The fault is introduced at 0.5 s when the system is running at steady state. The residual characteristics of the DC bus voltage and current can be calculated by the MMC-HVDC system residual state Eq. (13), as shown in Fig. 3. The baseline reference points of the HVDC fault observer output voltage and current are zero, which can be seen by comparing Figs. 2 and 3. When the system operates normally, taking into account the existing uncertainties and various random disturbances, residual curve should fluctuate within a limited range. From Fig. 3 it can be seen that, after a system fault, the system output curves (the DC bus voltage and current) significantly deviate from zero and their normal



**Fig. 7** Residual error curve during three phase to ground fault

bands. The system's fault diagnostic threshold can be calculated according to Theorem 4. If the residual waveform fluctuates within the calculated threshold, it is judged that the system is operating normally. If the residual waveform exceeds the calculated threshold, a fault is detected and immediate protection action should be taken. Furthermore, the fault identification and fault estimation can also be studied according to the residual waveform. As seen from the simulation, when  $t > 0.52$  s, it detects a fault in the system.

### Phase-AB to ground fault

The waveforms during phase-AB to ground fault are shown in Fig. 4 where the fault is introduced at 0.5 s. Due to the existence of various disturbances and uncertainties in the system, measurement noise is inevitably introduced when measuring system output. The residual voltage and residual current waveforms are shown in Fig. 5. According to Theorem 4, the fault detection threshold is  $J_{th} = 0.136 * 104$ . As seen from the simulation, when  $t > 0.52$  s, the fault is detected.

### Three phase to ground fault

The waveforms during three phase to ground fault is shown in Fig. 6. The fault is again introduced at 0.5 s. The residual voltage and residual current waveforms calculated according to residual system state equation are shown in Fig. 7. According to Theorem 4, the fault detection threshold is  $J_{th} = 2.62 * 104$ . As seen from the simulation, when  $t > 0.52$  s, the system fault is detected.

## Conclusions

In this paper, a robust fault diagnosis method is proposed to detect system fault in MMC-HVDC power transmission systems. The advantage of the proposed method is that the state observer considers the system uncertainties and fault sensitivity. Therefore, the proposed method can quickly achieve system fault diagnosis and accurately complete fault identification. The simulation results have proved the effect of robust fault diagnosis.

### Authors' contributions

ZQY analyzed and proposed the robust fault diagnosis method. QZ, PC and QZ completed the simulations on RT-LAB and the written of this paper. ALL the authors read and approved the final manuscript.

### Competing interests

The authors declare that they have no competing interests.

### Author details

<sup>1</sup>Xuchang KETOP Electrical Research Institute, Xuchang, China. <sup>2</sup>XJ Electric Co., Ltd, Xuchang, China.

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