Fault-Tolerant/Intrusion-Tolerant Control Of Island AC Microgrid System

Wang Jun¹, Wang BingQiang² and Feng Tian³

¹College of Electrical and Information Engineering, Lanzhou Univ. of Tech., Lanzhou, 730050, China
²Key Lab of Advanced Control for Industrial Process in Gansu Province, Lanzhou, 730050, China
³Key Lab of Advanced Control for Industrial Process in Gansu Province, Lanzhou, 730050, China

*Corresponding author’s e-mail: wangj@lut.edu.cn

Abstract. Aiming at arbitrary failures of actuators and network attacks, the design problems of passive fault-tolerant/intrusion-tolerant robust $H_\infty$ controllers for island AC microgrid inverter systems are studied. The controller has a good ability to suppress external limited energy disturbances. First, a closed-loop system model including actuator failure was established; then, the network attack on the actuator is described as a special external interference to design a $H_\infty$ robust passive fault-tolerant/intrusion-tolerant controller, and the Lyapunov equation and linear matrix inequality are used to obtain sufficient conditions for the progressive stability of the closed-loop fault system. Finally, the feasibility and effectiveness of the designed control law are verified through MATLAB simulation.

1. Preface

Microgrid is a small power generation and distribution system that organically combines distributed power sources, loads, energy storage devices, inverter systems, and monitoring and protection devices [1,2]. As a tool for connecting distributed power sources and microgrids, inverters provide a favorable guarantee for people to make full use of renewable energy. Using LCL inverters as control objects has become a hot spot in the field of microgrid research in recent years.

In island mode, the basic condition for stable operation of microgrid is that the micro source must provide a stable voltage and frequency environment and keep it within an allowable range [3]. The power and control system of the power generation system is generally undertaken by a high-power inverter. If the inverter fails to obtain technical diagnosis and repair, it will inevitably cause irreparable economic losses and safety risks. The study found that the inverter is one of the weak links of microgrid reliability [4]. In this article, the inverter part is regarded as an actuator. Therefore, research on the reliability of island AC microgrid inverters has always attracted the attention of scholars. Fault-tolerant control is an effective method to improve the reliability of inverter operation. With the increasing requirements for reliability and safety of control systems, fault diagnosis and fault-tolerant control have become an important branch of the control field [5,6]. There are two methods for fault diagnosis: fault detection and isolation and fault estimation. Compared with fault detection and isolation, fault estimation can obtain fault value, which can be directly applied to fault-tolerant control, and has a broader application prospect.
Moreover, fault estimation essentially includes fault detection and isolation. Therefore, fault estimation and fault-tolerant control of the system has important theoretical research significance and practical application value [7-9]. Literature [10] proposes to construct a Bayesian network for fault diagnosis of inverter switching elements without changing the topology of the inverter circuit for multi-level inverters. Then, the active fault-tolerant control method is used to reconstruct the variable carrier and modulating wave voltages so that the output voltage can still meet the stable operation of the system. Literature [11] considers the uncertain faults and external interference faults of the photovoltaic LCL inverter system, and proposes a continuous integral sliding mode fault-tolerant control method based on a high-order sliding mode observer, so that the system can still operate stably under fault conditions.

In addition, since the microgrid is also a cyber-physical integration system (CPS), malicious cyber-attacks may pose a potential threat to the safe and reliable operation of the microgrid system. In recent years, major accidents caused by cyber-attacks on power systems have occurred frequently. The literature [12] puts forward suggestions for the follow-up research directions for the various types of network attacks that power CPS may face, while considering the risks of the information side and the physical side. The above-mentioned documents are all researches on fault tolerance or intrusion tolerance alone, and there is no report on the comprehensive consideration of fault tolerance and network attack intrusion tolerance. Therefore, it is very important to design a fault-tolerant / intrusion tolerant controller for the actuator failure and network attack.

This paper considers the most common malicious attack that degrades or tampered with the output of the microgrid system, that is, the data integrity attack [13]. Aiming at the uncertain island AC microgrid system, when the actuator may fail and be attacked by the network, and when there is a limited external energy disturbance, a $H_\infty$ model-based passive fault-tolerant/intrusion-tolerant robust control method is proposed. First, a closed-loop model of an AC microgrid system with uncertain islands that integrates faults and attacks was established. Secondly, in the case of possible failure of the actuator and network attacks, a fault-tolerant/intrusion-tolerant controller is designed to ensure the stability of the closed-loop system with uncertain parameters and limited external energy disturbances. Finally, the effectiveness of the proposed method is verified by simulation.

2. Problem description

2.1 The main circuit topology of island inverter

The main circuit topology of the island AC microgrid system is shown in Figure 1 [3]. The inverter includes a DC input voltage source, 6 fully-controlled power devices IGBT, resistance on the power transmission line of the microgrid, small resistance on the switching device and LCL low-pass filter. $U_{dc}$ replace micro power sources in micro grids (renewable energy such as photovoltaics and wind power); The equivalent series resistance of each phase switching device, the low-voltage equivalent resistance of the inverter output to the AC bus of the microgrid, and the damping resistance of the LCL filter are respectively $R_1$, $R_2$ and $R_i$. $i_1$ and $i_2$ are the current flowing through the inductor $L_1$ and the inductor $L_2$ respectively; $U_i$ is the output voltage of the energy storage device.
2.2 Fault model of island inverter

Assuming that the system is operating stably in an ideal state, according to the structural topology of the island system, considering the power loss and switching loss on the transmission line, and the mathematical model of the system is established. According to Kirchhoff’s voltage and current law, and using Clark transformation to eliminate the common mode component in the three-phase, the continuous mathematical model of the island AC microgrid LCL inverter can be obtained [6].

\[
\begin{align*}
L_1 \frac{di_1}{dt} & = U_0 - R_i - U_c - R(i_1 - i_2) \\
L_2 \frac{di_2}{dt} & = U_c + R'(i_1 - i_2) - R_i i_2 - U_0 \\
C \frac{dU_0}{dt} & = i_1 - i_2 
\end{align*}
\]

In the formula, \(i_1\) -- the output current of the inductor \(L_1\); \(i_2\) -- the output current of the inductor \(L_2\); \(U_0\) -- the output voltage of the inverter; \(U_c\) -- the terminal voltage of the capacitor \(C\); \(U_0\) -- the output voltage of the energy storage device.

In the actual power system, there are some uncertain factors inside and outside the system, which affect the normal operation of the system. This article will consider that the uncertainty within the system is caused by inductance \(L_i\). Considering the situation that the internal uncertainty of the island AC microgrid inverter system and the limited external energy disturbance exist simultaneously. The state space model of the system is:

\[
\begin{align*}
\dot{x}(t) & = (A + \Delta A)x(t) + (B + \Delta B)u(t) \quad w(t) \\
y(t) & = Cx(t)
\end{align*}
\]

In the formula, \(x(t) = [i_1 \quad i_2 \quad U_c]^T\) --system status, \(u(t) = [U_0 \quad U_1]^T \in \mathbb{R}^n\) --control input; \(w(t) \in \mathbb{R}^n\) -- the bounded energy disturbance outside the system; \(y(t) = [i_1 \quad i_2 \quad U_c]^T \in \mathbb{R}^n\) -- the modulated output; \(A, B, C, B_i\) are known matrices of suitable dimensions. \(\Delta A, \Delta B\) are time-varying parameter uncertainty matrices with bounded norm.

Where,
2.3 The establishment of a closed-loop system model under both faults and attacks

Considering the uncertain linear microgrid controlled object model (2), actuator failure and network attack, the following closed-loop DER failure and attack coexisting model can be obtained:

\[
\begin{bmatrix}
\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}_1\mathbf{w}(t) \\
\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)
\end{bmatrix}
\]

Where, \(\mathbf{A} = \mathbf{A} + \mathbf{\Delta A}\), \(\mathbf{B} = \mathbf{B} + \mathbf{\Delta B}\). For output feedback and actuator-side network attacks, its feedback control law:

\[
u(t) = F\mathbf{K}\mathbf{y}(t) + \mathbf{\alpha}(t)\mathbf{a}^o(t)
\]

Among them: \(\mathbf{a}^o(t)\) -- the network attack on the actuator side, is a Markovian random process with a value of 1 or 0. That is, \(\mathbf{\alpha}(t) = 1\) means the actuator network attack \(\mathbf{a}^o(t)\) has occurred, and \(\mathbf{\alpha}(t) = 0\) means no actuator network attack \(\mathbf{a}^o(t)\) has occurred; \(F\) -- the status of the actuator channel, and its form is: \(F = \text{diag}\{f_1,f_2,\ldots,f_n\}\). Among them, \(f_i = 1\) -- the \(i\)-th actuator is normal, \(f_i \in (0,1)\) -- partial failure of the \(i\)-th actuator, \(f_i = 0\) -- the \(i\)-th actuator completely fails, \(F \in \Omega\) - - the set of all possible actuator failure modes [17], \(\Omega\) -- the diagonal matrix combination (except \(F = 0\)) of various combinations of 0 to 1 for the elements of the actuator switch matrix \(F\).

Incorporating equation (4) into equation (3) and sorting it out, we can get:

\[
\dot{x}(t) = [\mathbf{A} + \mathbf{BFKC} + \mathbf{\Delta A}(t) + \mathbf{\Delta B}(t)\mathbf{FKC}]\mathbf{x}(t) + (\mathbf{B} + \mathbf{\Delta B})\mathbf{x}(t)
\]

2.4 Related lemma

Lemma 1 [14] (Schur’s complement lemma): Given a symmetric matrix \(\mathbf{S} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix}, \mathbf{S} \in \mathbb{R}^{n \times n}\). The following matrix inequalities are equivalent:

1) \(\mathbf{S} < \mathbf{0};\)  
2) \(\mathbf{S}_{11}, \mathbf{S}_{22} - \mathbf{S}_{12}^T\mathbf{S}_{11}\mathbf{S}_{22}^{-1}\mathbf{S}_{12} < \mathbf{0};\)  
3) \(\mathbf{S}_{22}, \mathbf{S}_{11} - \mathbf{S}_{12}\mathbf{S}_{22}^{-1}\mathbf{S}_{12}^T < \mathbf{0}\).

Lemma 2 [16]. For a given matrix \(\mathbf{X}\) and \(\mathbf{Y}\) of suitable dimensions, the following inequality holds:

\(\mathbf{X}^T\mathbf{Y} + \mathbf{Y}^T\mathbf{X} \leq \mathbf{X}^T\mathbf{X} + \mathbf{Y}^T\mathbf{Y}\)

Lemma 3 [16]. If \(n \times m\) -order matrix \(\mathbf{\Delta A}\) satisfies \(\mathbf{\Delta A} < \mathbf{D}\), then \(\mathbf{\Omega}(\mathbf{D}) \geq \mathbf{\Delta A}\mathbf{D}^T\), \(\mathbf{\Gamma}(\mathbf{D}) \geq \mathbf{\Delta A}\mathbf{D}^T\). Where

\[
\mathbf{\Omega}(\mathbf{D}) = \begin{cases} \|\mathbf{DD}^T\|_n, & \|\mathbf{DD}^T\|_n < n \cdot \text{diag}\{\mathbf{DD}^T\} \\
\text{n \cdot diag}\{\mathbf{DD}^T\}, & \text{otherwise} \end{cases}
\]

\[
\mathbf{\Gamma}(\mathbf{D}) = \begin{cases} \|\mathbf{DD}^T\|_n, & \|\mathbf{DD}^T\|_n < n \cdot \text{diag}\{\mathbf{DD}^T\} \\
\text{m \cdot diag}\{\mathbf{DD}^T\}, & \text{otherwise} \end{cases}
\]
Among them, \( D \) -- a real constant matrix with non-negative elements, the same dimension as \( \Delta A \). Here \( |\Delta|<\overline{\Delta} \) means: \( |e_{ij}| \leq \overline{e_{ij}}(i, j = 1, 2, \cdots, N) \), \( e_{ij} \) and \( \overline{e_{ij}} \) are the elements in the \( i-th \) row and \( j-th \) column of matrix \( \Delta \) and \( \overline{\Delta} \). \( \|\cdot\| \) is the maximum singular value norm.

3. Main results
Aiming at the uncertain island AC microgrid inverter system where actuator failure and network attack coexist, the design goals are: Seek the output feedback matrix \( K \) to make the disturbing uncertain closed-loop system (5) meet the following three conditions under the possible actuator failure and the output actuator network attack:

1) When there is no attack and no disturbance, the disturbing uncertain system (5) is gradually stable;
2) When there is disturbance without attack, that is \( \alpha(t) = 0 \). For zero initial conditions, when any \( w(t) \neq 0 \), satisfies \( \|z(t)\|_{2} \leq \gamma_{1}^{|w(t)|}_{2} \), where \( \gamma_{1} \) is the disturbance suppression rate under a given no attack;
3) When there is attack and disturbance, that is \( \alpha(t) \neq 0 \), satisfies \( \|z(t)\|_{2} \leq \gamma_{2}^{|w(t)|}_{2} \), where \( \gamma_{2} \) is the disturbance suppression rate under a given attack.

Theorem 1: If there is a positive definite symmetric matrix \( A \) and a normal number \( B \), the following linear matrix inequality holds:

\[
\begin{bmatrix}
\Sigma_{11} & C^T P B & PB & P \Omega^{1/2}(M) \alpha^T (a^s)^T & PB \beta & PB_b
\end{bmatrix} \leq 0 \quad (6)
\]

Where, \( \Sigma_{11} = A^T P + PA + \Omega(D) + C^T C \), Then there is the output feedback control law (4), which makes the uncertain island AC microgrid system gradually stable under limited energy disturbance, and the gain matrix \( K = -\lambda B^T P \) of the output feedback controller with fault tolerance/intrusion tolerance, where, \( \beta = \frac{1}{\sqrt{2\lambda^2}} \).

Proof: Construct a Lyapunov function, which is a positive definite symmetric matrix \( P \) (for convenience, time \( t \) is omitted)

\[ V(t) = x^T P x \quad (7) \]

Derivation of equation (7) along the closed loop system (5), we can get:

\[ \dot{V}(t) = x^T P \dot{x} + x^T \dot{P} x = [(A + BFKC + \Delta A + \Delta BFKC)x + (B + \Delta B)\alpha a^s + B_i w] P x \]

\[ + x^T P[(A + BFKC + \Delta A + \Delta BFKC)x + (B + \Delta B)\alpha a^s + B_i w] \]

\[ = x^T (A^T P + PA)x + x^T (C^T K^T B^T P + PBFKC)x + x^T PB_i w + x^T (\Delta A^T P + \Delta A)x + w^T B_i^T P x \]

\[ + x^T (C^T K^T \Delta B^T P + \Delta PBFKC)x + (a^s)^T \alpha^T B^T P x + (a^s)^T \alpha^T \Delta B^T P x + x^T P B a a^s + x^T P \Delta B a a^s \]

According to Lemma 2, several terms in formula (8) can be transformed as follows:
\[
C^T K^T F^T B^T P + PBFKC \leq C^T K^T KC + PBB^T P \\
\Delta A^T P + P\Delta A \leq PP + \Delta A\Delta A^T \\
C^T K^T F^T \Delta B^T P + P\Delta BFKC \leq C^T K^T KC + P\Delta B\Delta B^T P \\
(a^\alpha)^T \alpha^\alpha B^T Px + x^T PB\alpha^a \leq (a^\alpha)^T \alpha^\alpha \alpha^a + x^T PBB^T Px \\
(a^\alpha)^T \alpha^\alpha \Delta B^T Px + x^T PB\alpha^a \leq (a^\alpha)^T \alpha^\alpha \alpha^a + x^T P\Delta B\Delta B^T Px 
\]

Putting (9)-(13) into equation (8) can get:
\[
\left(\begin{array}{cc}
V_{x} & x^T Cx \\
\alpha^\alpha & \alpha^\alpha
\end{array}\right) + 2\left(\begin{array}{c}
B^T Px + B^T wP^T x \\
\alpha^\alpha \alpha^a + x^T P\Delta B\Delta B^T Px
\end{array}\right) \leq \left(\begin{array}{c}
\alpha^\alpha \alpha^a + \alpha^\alpha \alpha^a + x^T P\Delta B\Delta B^T Px
\end{array}\right)
\]

When considering the gradual stability of the closed-loop system, without considering disturbances and attacks, that is, let \( w(t) = 0 \) and \( \alpha(t) = 0 \) in (14), then (13) can be reduced to
\[
\dot{V}(x) \leq x^T(A^T P + PA + 2C^T K^T KC + 2PBB^T P + PP + \Delta A\Delta A^T)Px
\]

From Lemma 3: \( \Delta A\Delta A^T \leq \Omega(D) \), \( \Delta B\Delta B^T \leq \Omega(M) \). Let \( K = -\beta B^T P \), Then substitute it in (15) to get
\[
\dot{V}(x) \leq x^T(A^T P + PA + 2\beta^2 C^T PBB^TPC + 2PBB^TP + PP + \Omega(D) + 2P\Omega(M))Px
\]

Equation (17) is equivalent to
\[
A^T P + PA + 2\beta^2 C^T PBB^TPC + 2PBB^TP + PP + \Omega(D) + 2P\Omega(M)P \leq 0
\]

Turning (18) into a linear matrix inequality using Schur's complement lemma, we have:
\[
\begin{bmatrix}
A^T P + PA + \Omega(D) & C^T PB & PB & P \Omega^{\frac{1}{2}} (M) \\
* & -\left[\frac{1}{2\beta^2}\right] & 0 & 0 \\
* & * & -2I & 0 \\
* & * & * & -I \\
* & * & * & -2I
\end{bmatrix} \leq 0
\]

So when (18) holds, condition 1) is satisfied.

Let's find a sufficient condition to satisfy condition 3). Define performance indicators:
\[
J = \int_0^\infty \left(y^T y - \gamma^2 w^T w\right)dt
\]

On account of
\[
J = \int_0^\infty \left(y^T y - \gamma^2 w^T w + \hat{V}\right)dt - \int_0^\infty \dot{V} dt < \int_0^\infty \left(y^T y - \gamma^2 w^T w + \hat{V}\right)dt
\]

Therefore, a sufficient condition for \( J \leq 0 \) is \( x^T Cx - \gamma^2 w^T w + \hat{V} \leq 0 \), that is
\[
x^T(A^T P + PA + 2\beta^2 C^T K^T KC + 2PBB^TP + PP + \Omega(D) + 2P\Omega(M)P + 2(a^\alpha)^T \alpha^\alpha \alpha^a + w^T B^T Px + x^T PBw + x^T Cx - \gamma^2 w^T w = \left[\begin{array}{c}
x^T \\
w^T
\end{array}\right] \Omega \left[\begin{array}{c}
x^T \\
w^T
\end{array}\right] + 2(a^\alpha)^T \alpha^\alpha \alpha^a \leq 0
\]
Where, 
\[
\Omega = \begin{bmatrix}
\Omega_{11} & PB_B \\
* & -\gamma^2 I
\end{bmatrix},
\Omega_{11} = A^T P + PA + 2C^T K^T KC + 2PBB^T P + PP + \Omega(D) + 2P\Omega(M)P + C^T C
\]
Using Schur's supplementary lemma, and then let \( \beta = \frac{1}{(2\lambda^2)} \), inequality (22) can be reduced to inequality
(6) in the theorem, the inequality in the theorem includes equation (19), so when the inequality in the theorem holds, condition 1), condition 2 ) And condition 3) are met at the same time.

Completed

4. Simulation examples

The linearization model of the island AC microgrid inverter system with uncertainty is set as:

\[
A = \begin{bmatrix}
-3 & 1 & -2 \\
1 & -1 & 2 \\
2 & -2 & 0
\end{bmatrix},
B = \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix},
C = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix},
B_i = \begin{bmatrix}
0 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]

\[
\Delta A = \begin{bmatrix}
1.3 \sin(t) & -1.1 \sin(t) & 0 \\
-0.8 \cos(t) & 1.8 \cos(t) & 0 \\
0 & 0 & 0
\end{bmatrix},
\Delta B = \begin{bmatrix}
1.2 \sin(t) & -0.5 \sin(t) & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

From Lemma 3, let
\[
\Omega(D) = \begin{bmatrix}
-1.378 & 0 & 0 \\
0 & -2.322 & 0 \\
0 & 0 & 0
\end{bmatrix},
\Omega(M) = \begin{bmatrix}
1.32 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

When there is a bounded energy disturbance, set
\[
w(t) = \begin{bmatrix}
\cos(2 pi t) \exp(-0.3 t) \\
\cos(2 pi t) \exp(-0.3 t)
\end{bmatrix}, t \in [5,10]
\]

For actuators normal or other fault distribution and severity, take \( F_i = \text{diag}\{1,1\} \), \( F_2 = \text{diag}\{0.2,0.8\} \), and \( F_3 = \text{diag}\{1,0\} \) to represent the normal inverter on the distributed power supply side and the energy storage device side, and the partial failure of the distributed power supply side and the energy storage device inverter. And the inverter of the energy storage device fails completely. In the simulation, assume that the network attack \( a^e(t) \) is a white noise sequence that obeys \( N(0,1,0.01) \). Consider the existence of cyber-attacks, namely \( a(t)=1 \). Let the initial state
\[
x(0) = \begin{bmatrix}
10 \\
10 \\
220
\end{bmatrix}
\]

1) The situation where the controller has passive fault tolerance/intrusion tolerance
   For failure modes \( F_1, F_2, F_3 \), take \( \gamma_i=1.0344 \), and use the feasp function in the MATLAB tool software to solve the inequality (4), we can get \( \beta=0.0556 \),
   \[
P = \begin{bmatrix}
0.3318 & -0.1139 & -0.2057 \\
-0.1139 & 0.3429 & 0.2798 \\
-0.2057 & 0.2798 & 0.4261
\end{bmatrix},
\lambda=3.002, K = \begin{bmatrix}
-0.3432 & 0.1178 & 0.2128 \\
-0.1178 & 0.3547 & 0.2894
\end{bmatrix}
\]

   For closed-loop system simulation, when the actuator fails and there is a network attack, the zero-input state response curve of the controller with passive fault tolerance/intrusion tolerance is shown in Figure 2~Figure 4.
It can be seen from Figure 2~Figure 4 that when the controller has passive fault tolerance/intrusion tolerance, in the case of actuator failure and network attack coexisting, the unstable and uncertain island AC microgrid inverter system gradually progresses stable. It shows that the designed controller has good fault tolerance/intrusion tolerance and good disturbance rejection performance.

2) The situation where the controller has fault tolerance and no intrusion tolerance

Regardless of network attack, namely $\alpha(t)=0$, for faults $F_1$, $F_2$ and $F_3$, the corresponding $\gamma^2=1.0132$ when these three faults are met at the same time can be obtained, and the following feedback gain matrix $K$ can be obtained:

$$
K = \begin{bmatrix}
-0.4132 & 0.1418 & 0.2561 \\
-0.1418 & 0.4270 & 0.3484
\end{bmatrix}
$$

When a partial failure of the actuator occurs, that is $F_2 = \text{diag} \{0.2, 0.8\}$, Figure 5~Figure 7 respectively show the response of the system zero input state $x_1, x_2, x_3$ when the controller has fault tolerance and no intrusion tolerance under the same network attack curve:
As can be seen in Figure 5–Figure 7, the state component $x_1$ oscillates from the beginning, and the oscillation amplitude is relatively large; $x_2$ and $x_3$ oscillate after 1.5 seconds, of which $x_2$ has the most severe amplitude in 2–5 seconds, 8–12 seconds, and 14–18 seconds; $x_3$ has a smaller oscillation amplitude. In general, the entire system cannot be restored to a balanced state.

Combining Figures 2–7, it fully shows that even if the system has actuator failures and network attacks, the passive fault-tolerant/intrusion-tolerant controller designed in this paper can not only effectively tolerate actuator failures, but also effectively tolerate network attacks. And also suppressing the influence of disturbance.

5. Conclusion

Aiming at the island AC microgrid system, when there are parameter uncertainties inside the system, bounded energy disturbances outside the system, possible failures of actuators, and network attacks, the design of a passive fault-tolerant/intrusion-tolerant robust $H_\infty$ controller is studied. The Lyapunov function is used to deduce the sufficient conditions to ensure that the control system is progressively stable when the actuator fails and is attacked by the network; it has good suppression performance; and the LMI method is used to obtain the passive fault-tolerant/intrusion-tolerant controller design method; Finally, MATLAB software is used to verify the effectiveness and feasibility of the method described in the article. The results show that the proposed method has obvious control advantages and improves the safety and reliability of the system.

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