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Secure Event-based Control for Networked Power System under Cyber-Attacks#

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ABSTRACT

This paper investigates the event-based secure control problem for networked power system subject to stochastic cyber-attacks. In order to make more effective use of network resources, an adaptive event-triggered mechanism (AETM) is developed, which differs from previous deterministic ETMs in that the designed trigger mechanism herein is based on stochastic dynamic variables. Moreover, the communication channel is contemplated for potential false data injection (FDI) attacks, while also considering the security performance of the networked power system. Then, the sufficient conditions for the system to satisfy the $\mathcal{H}_\infty$ performance index and mean-square exponential stable are given by using the Lyapunov stability theory, and the solvability of the security controller is obtained based on linear matrix inequalities (LMIs). Finally, the effectiveness of the proposed control method is verified by a simulation example.

Keywords: power systems, secure control, adaptive event-triggered mechanism, FDI attacks

1. INTRODUCTION

The power system consists of generation, transmission, distribution, and consumption [1]. As modern power systems advance and the demand for high-quality electricity increases, traditional dedicated communication networks are no longer sufficient. Open communication infrastructures now enable large-scale information exchange, facilitating measurement transmission from remote telemetry units to area controllers . Additionally, open communication networks significantly enhance monitoring, control, and dispatching in critical industrial sectors like equipment manufacturing, transportation, and smart buildings. Consequently, network security for power systems is becoming increasingly urgent.

With the consideration of network congestion and limited communication bandwidth resources, an adaptive event-triggered communication mechanism is adopted. Compared with the traditional time-triggered scheme that transmits signals at a fixed communication rate, under the event-triggered communication scheme, signals are released only when a pre-specified threshold is met, thus effectively reducing the transmission burden on the network and maintaining system performance. To lower the triggering frequency, AETM have been proposed in [2], which adjust the threshold parameter dynamically.

On the other hand, apart from concerns regarding limited communication capacity, ensuring security of communication channel is crucial as it may be vulnerable to malicious cyber-attacks such as denial-of-service (DoS) attacks and deception attacks [3]. DoS attacks aim to prevent data transmission while deception attacks seek to manipulate the original information, both of which will have unpredictable negative impacts on signal transmission. In response to FDI attacks, significant focus has been placed on secure control strategies [4]. Reference [5] explored a secure control approach with an event-triggered mechanism for cyber-physical systems facing unknown FDI attacks. Li et al. [6] developed an event-triggered consensus controller for multi-agent systems dealing with FDI attacks and uncertainties. Additionally, [7] tackled the resilient load frequency control issue in the context of FDI and DoS attacks.

Inspired by the aforesaid investigations, this work focuses on the event-based secure control problem for networked power system under FDI attack. The main contributions are highlighted as follows:

1) An enhanced AET scheme adjusts system convergence speed by varying the threshold parameter and extends execution time during normal operations.

2) The mean-square exponential stability of the system is determined and $\mathcal{H}_\infty$ performance is satisfied by employing some novel matrix transformation techniques and singular value decoupling methods.

The rest of the paper is as follows: Section 2 presents some mathematical models. Section 3 gives the results of stability analysis, performance analysis and controller gain solution of the power system. Section 4 demonstrates the validity of the results obtained

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through a simulation example. Finally, Section 5 concludes the paper.

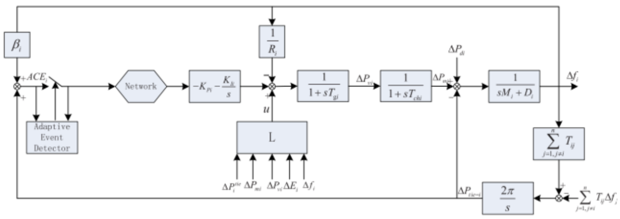

Fig. 1 Framework of the multi-area power system of i-th area

2. PROBLEM STATEMENT

2.1 Power system model

In this paper, we consider a one-area LFC system, which can be seen from Fig. 1 when $T_{ij} = 0$ for $i \neq j$. The dynamic model is formulated as follows:

$$\begin{cases} \dot{x}(t) = \mathbb{A}x(t) + \mathbb{B}u(t) + \mathbb{F}\omega(t) \\ y(t) = \mathbb{C}x(t) \end{cases} \tag{1}$$

where $x(t) = col\{\Delta f, \Delta P_v, \Delta P_m\}$, $y(t) = \text{ACE}$, $\omega(t) = \Delta P_d$, and

$$\mathbb{A} = \begin{bmatrix} -\frac{D}{M} & 0 & \frac{1}{M} \\ -\frac{1}{T_g R} & -\frac{1}{T_g} & 0 \\ 0 & \frac{1}{T_{ch}} & \frac{1}{T_{ch}} \end{bmatrix}, \quad \mathbb{B} = \begin{bmatrix} 0 & \frac{1}{T_g} & 0 \end{bmatrix}^T$$

$$\mathbb{F} = \begin{bmatrix} -\frac{1}{M} & 0 & 0 \end{bmatrix}^T, \quad \mathbb{C} = \begin{bmatrix} \beta & 0 & 0 \end{bmatrix}$$

where Δf denotes the frequency deviation, ΔP_v is the valve position deviation, ΔP_m represents the generator mechanical output, and ΔP_d means the load perturbation. T_g and T_{ch} indicate the time constant of the governor and the time constant of the turbine, respectively. D, M, R, and β are shown as generator damping coefficients, the moments of inertia of the generator, the speed drop, and the frequency bias factor drop, respectively.

By virtue of the absence of net tie-line power exchange, the area control error (ACE) can be defined in the one-area LFC system can be redefined as $\text{ACE} = \beta\Delta f$. Then, redefine $x(t) = col\{\Delta f, \Delta P_v, \Delta P_m, \int \text{ACE}\}$, $y(t) = col\{\text{ACE}, \int \text{ACE}\}$. Thus, system (1) can be reformulated as:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F\omega(t) \\ y(t) = Cx(t) \end{cases} \tag{2}$$

where

$$A = \begin{bmatrix} -\frac{D}{M} & 0 & \frac{1}{M} & 0 \\ -\frac{1}{T_g R} & -\frac{1}{T_g} & 0 & 0 \\ 0 & \frac{1}{T_{ch}} & \frac{1}{T_{ch}} & 0 \\ \beta & 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{1}{T_g} \\ 0 \\ 0 \end{bmatrix}$$

$$F = \begin{bmatrix} -\frac{1}{M} & 0 & 0 & 0 \end{bmatrix}^T, \quad C = \begin{bmatrix} \beta & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

2.2 AET mechanism

For the purpose of fully utilizing the restricted bandwidth resources and reducing communication network transmission load, an AET mechanism is considered as

$$\begin{aligned} t_{k+1}h = t_k h + min\{lh \,|\, [y(t_k h + lh) - y(t_k h)]^T \Phi \\ \times [y(t_k h + lh) - y(t_k h)] > \eta(t_k h) y^T(t_k h) \Phi y(t_k h)\} \end{aligned} \tag{3}$$

where $t_k h$ is the kth triggering instant, $y(t_k h)$ means the latest transmitted data and matrix Φ needs to be determined. The threshold parameter $\eta(t_k h) \in [\eta_m, \eta_M]$, $\eta(0) = \eta_0$, is adjusted to the deviation of the latest output signal:

when $||y(t_k h)|| - ||y(t_{k-1} h)|| > 0$,

$$\eta(t_k h) = \eta(t_{k-1} h)(1 - \frac{2}{\pi}\arctan(\frac{\| y(t_k h) - y(t_{k-1} h) \|}{\| y(t_k h) \|})), \tag{4}$$

when $||y(t_k h)|| - ||y(t_{k-1} h)|| \leq 0$,

$$\eta(t_k h) = \eta(t_{k-1} h)(1 + \frac{2}{\pi}\arctan(\frac{\| y(t_k h) - y(t_{k-1} h) \|}{\| y(t_k h) \|})), \tag{5}$$

Define $[t_k h + \sigma_k, t_{k+1} h + \sigma_{k+1}) = U_{i=0}^{d} \mathfrak{A}_i$, where $\mathfrak{A}_0 = [t_k h + \sigma_k, t_k h + \bar{\sigma} + h)$, $\mathfrak{A}_i = [t_k h + ih + \bar{\sigma}, t_k h + ih + h)$, and $\mathfrak{A}_d = [t_k h + dh + \bar{\sigma}, t_{k+1} h + \sigma_{k+1})$. Moreover, it is possible to define

$$\sigma(t)=\begin{cases}t-t_kh, & k\in\mathfrak{A}_0,\\ t-t_kh-ih, & k\in\mathfrak{A}_i,\\ t-t_kh-\mathrm{d}h, & k\in\mathfrak{A}_d,\end{cases} \quad (6)$$

where for each $t\in[t_kh+\sigma_k, t_{k+1}h+\sigma_{k+1})$, one has $\sigma_m\le\sigma(t)\le\bar{\sigma}+h=\sigma_m$. Then, the error is defined as

$$e(t)=\begin{cases}0, & t\in\mathfrak{A}_0\\ y(t_kh)-y(t_kh+ih), & t\in\mathfrak{A}_i\\ y(t_kh)-y(t_kh+dh), & t\in\mathfrak{A}_d\end{cases} \quad (7)$$

2.3 FDI Attack model- based control scheme

In view of the open wireless communication network channel, the measurement output is susceptible to FDI attacks by malicious attackers, and the actual measurements are provided as

$$y(t)=y(t_kh)+\alpha(t)\varphi(y(t_kh)) \quad (8)$$

where $\alpha(t)$ obeys Bernoulli distribution with $E\{\alpha(k)\}=\bar{\alpha}$, false data $\varphi(y(t_kh))$ is a nonlinear function satisfying the $\|\varphi(y(t_kh))\|\le\|\mathcal{R}y(t_kh)\|$, and $\mathcal{R}$ is the given matrix.

Then, the real control input can be established as follows

$$u(t)=-K[\alpha(t)\varphi(y(t_kh))+y(t-\sigma(t))+e(t)] \quad (9)$$

where $K=[K_P \quad K_I]$ is the controller gain to be designed.

Therefore, system (2) can be reconstructed as

$$\begin{cases}\dot{x}(t)=Ax(t)-BKe(t)-BKCx(t-\sigma(t))\\ \qquad -\alpha(t)BK\varphi(y(t_kh))+F\omega(t)\\ y(t)=Cx(t)\end{cases} \quad (10)$$

Definition 1 [3]: The system (10) is deemed mean-square exponentially stable (MSES), if there exist scalars $\varrho\in(0,\infty)$, $\epsilon\in(0,\infty)$ when $\omega(t)=0$ such that the inequality below is satisfied

$$\mathbb{E}\{\|x(t)\|^2\}\le\varrho\mathbb{E}\{\|x(t_0)\|^2\}e^{-\epsilon t}, \quad \forall t\ge 0$$

Definition 2 [4]: For a prescribed performance level $\gamma>0$, under zero initial condition, if the system (10) is MSES while satisfying

$$\mathbb{E}\left(\int_0^\infty y(t)^Ty(t)dt\right)\le\mathbb{E}\left(\gamma^2\int_0^\infty w(t)^Tw(t)dt\right)$$

then, the system (10) meets $\mathcal{H}_\infty$ performance.

Lemma 2 [7]: Given that Γ is full column rank with singular value decomposition $\Gamma=\mathfrak{D}[\mathfrak{L} \quad 0]\mathcal{Z}$, where $\mathfrak{D}$ and $\mathcal{Z}$ are the orthogonal matrices, and $\mathfrak{L}$ is a diagonal matrix with nonnegative elements arranged in descending order on the diagonal. For a symmetric matrix $\mathcal{S}\in\mathbb{R}^{m\times m}$, there exists a matrix Y such that $\mathcal{S}\Gamma=\Gamma\mathrm{Y}$ if and only if $\mathcal{S}$ can be expressed as $\mathcal{S}=\mathfrak{D}\begin{bmatrix}\mathcal{S}_1 & 0\\ 0 & \mathcal{S}_2\end{bmatrix}\mathfrak{D}^T$, where $\mathcal{S}_1\in\mathbb{R}^{n\times n}$ and $\mathcal{S}_2\in\mathbb{R}^{(m-n)\times(m-n)}$.

3. MAIN RESULTS

Theorem 1: Given positive scalars $\bar{\alpha}$, h, η_M, δ, μ, λ and matrix $\mathcal{R}$, the system (10) is MSES with $\mathcal{H}_\infty$ performance, if there exist positive symmetric matrices *P*, *Q*, *R*, Φ, *K* and matrices *N*, $\mathcal{S}$, the following conditions hold

$$\Theta<0 \quad (11)$$

$$\begin{bmatrix}M & N\\ N^T & M\end{bmatrix}\ge 0 \quad (12)$$

where

$\Theta=[\Theta_{ij}]_{7\times7}$, $\Theta_{11}=Q+\mu P+C^TC-e^{-\mu h}M+2\mathcal{S}A$
$\Theta_{12}=e^{-\mu h}(M-N)+\mathcal{S}BKC$, $\Theta_{13}=e^{-\mu h}N$
$\Theta_{14}=P-\mathcal{S}+\lambda A^T\mathcal{S}$, $\Theta_{15}=\mathcal{S}BK$, $\Theta_{16}=\bar{\alpha}\mathcal{S}BK$
$\Theta_{17}=-\mathcal{S}F$, $\Theta_{23}=-e^{-\mu h}(2M+2N)$
$\Theta_{22}=-e^{-\mu h}(M+2N)+\eta_MC^T\Phi C+\delta C^T\mathcal{R}^T\mathcal{R}C$
$\Theta_{24}=\lambda C^TR^TB^TS^T$, $\Theta_{25}=\eta_MC^T\Phi+\delta C^T\mathcal{R}^T\mathcal{R}$
$\Theta_{33}=-e^{-\mu h}(M+Q)$, $\Theta_{44}=-\lambda\mathcal{S}+h^2R$
$\Theta_{45}=\lambda\mathcal{S}BK$, $\Theta_{46}=\bar{\alpha}\lambda\mathcal{S}BK$, $\Theta_{46}=-\lambda\mathcal{S}F$
$\Theta_{55}=-\Phi+\eta_M\Phi+\delta C^T\mathcal{R}^T\mathcal{R}$, $\Theta_{66}=-\delta I$
$\Theta_{77}=-\gamma^2I$

Proof: the Lyapunov function is constructed as

$$V(t)=x^T(t)Px(t)+\int_{t-h}^t e^{-\mu(t-s)}x^T(s)Qx(s)d$$
$$+h\int_{-h}^0\int_{t+\theta}^t e^{-\mu(t-s)}x^T(s)Rxx(s)d\theta \quad (13)$$

()

Along the trajectory of (10), we can calculate the derivation

$$\mathrm{E}\{\dot{V}(t)\}=E\{2x^T(t)P\dot{x}(t)+x(t)Qx(t)-\mu V(t)$$
$$+\mu x^T(t)Px(t)+h^2\dot{x}^T(t)R\dot{x}(t)$$
$$-e^{-\mu h}x^T(t-h)Qx(t-h)$$
$$-he^{-\mu h}\int_{t-h}^t\dot{x}^T(s)R\dot{x}(s)ds\} \quad (14)$$

By employing the inequality technique, one gets

$$-he^{-\mu h}\int_{t-h}^{t}\dot{x}^T(s)R\dot{x}(s)ds$$
$$\leq -e^{-\mu h}\begin{bmatrix} x(t)-x(t-\sigma(t)) \\ x(t-\sigma(t))-x(t-h)\end{bmatrix}^T \begin{bmatrix} M & N \\ N^T & M\end{bmatrix} \times \begin{bmatrix} x(t)-x(t-\sigma(t)) \\ x(t-\sigma(t))-x(t-h)\end{bmatrix} \quad (15)$$

Additionally, based on the formula (3), for $t \in [t_k h+\sigma_k, t_{k+1}h+\sigma_{k+1})$, it can be inferred that

$$\eta_M[e(t)+y(t-\sigma(t))]^T\Phi[e(t)+y(t-\sigma(t))] -e^T(t)\Phi e(t) > 0 \quad (16)$$

while taking into account the restriction of FDI attack, one has

$$y^T(t_k h)\mathcal{R}^T\mathcal{R}y(t_k h)-\varphi^T(y(t_k h))\varphi(y(t_k h)) \geq 0 \quad (17)$$

Based on (10), we can get

$$-2\mathrm{E}\{[x^T(t)+\lambda\dot{x}^T(t)]^T\mathcal{S}[\dot{x}(t)-Ax(t)-BKe(t) -BKCX(t-\sigma(t))-\alpha(t)BK\varphi(y(t_k h)) +F\omega(t)\}=0 \quad (18)$$

Therefore, combining (14)-(18), it yields that

$$E\{\dot{V}(t)+\mu V(t)+y^T(t)y(t)-\gamma^2\omega^T(t)\omega(t)\}$$
$$\leq E\{2x\text{^}T\,(t)Px\,\dot{}(t)+x(t)Qx(t)+\mu x\text{^}T\,(t)Px(t)$$
$$-e^{-\mu h}x^T(t-h)Qx(t-h)+h^2\dot{x}^T(t)R\dot{x}(t)$$
$$-e^{-\mu h}\begin{bmatrix} x(t)-x(t-\sigma(t)) \\ x(t-\sigma(t))-x(t-h)\end{bmatrix}^T \begin{bmatrix} \mathcal{M} & N \\ N^T & \mathcal{M}\end{bmatrix}$$
$$\times \begin{bmatrix} x(t)-x(t-\sigma(t)) \\ x(t-\sigma(t))-x(t-h)\end{bmatrix} -\gamma^2 w^T(t)w(t)$$
$$+\eta_M[e(t)+y(t-\sigma(t))]^T\Phi[e(t)+y(t-\sigma(t))]$$
$$-e^T(t)\Phi e(t)-\delta\varphi^T(y(t_k h))\varphi(y(t_k h))$$
$$+\delta y^T(t_k h)\mathcal{R}^T\mathcal{R}y(t_k h)+x^T(t)C^TCx(t)$$
$$\leq \xi^T(t)\Theta\xi(t) \quad (19)$$

where

$$\xi(t)=[x^T(t)\ \ x^T(t-\sigma(t))\ \ x^T(t-h)\ \ \dot{x}^T(t) \ \ e^T(t)\ \ \varphi^T(y(t_k h))\ \ \omega^T(t)]^T$$

Afterwards, it follows from (11)-(12) that

$$E\{\dot{V}(t)\} \leq E\{-\mu V(t)-y^T(t)y(t) +\gamma^2\omega^T(t)\omega(t)\} \quad (20)$$

Then, when $\omega(t)=0$ we can further have that

$$E\{\dot{V}(t)\} \leq E\{-\mu V(t)\} \quad (21)$$

By multiplying $e^{\mu t}$ by both sides of (20), we get

$$\mathrm{E}\{V(t)\} \leq e^{-\mu t}\,V(0) \quad (22)$$

Furthermore, according to equation (13), $\exists c_1 = c_1 = min\{\lambda_{min}(\mathrm{P})\}$, $c_2=\max\{\lambda_{max}(\mathrm{P})\}+h\lambda_{max}(Q)+\frac{h^2}{2}\lambda_{max}(\mathrm{R})$, which make the following inequalities hold

$$\mathbb{E}\{V(t)\} \geq c_1\mathbb{E}\{\|x(t)\|^2\} \quad (23)$$
$$\mathbb{E}\{\mathrm{V}(0)\} \leq c_2\mathbb{E}\{\|x(0)\|^2\} \quad (24)$$

Thus, it is deduced from (21)-(23) that

$$E\{||x(t)||^2\} \leq \frac{c_2}{c_1}e^{-\mu t}E\{||x(0)||^2\} \quad (25)$$

In accordance with Definition 1, the system (10) is considered as MSES.

Next, when $\omega(t)=0$, integrating both sides of inequality (19) from 0 to t under zero initial condition yields

$$\int_0^\infty y^T(t)y(t) \leq \int_0^\infty \gamma^2 w^T(t)w(t) \quad (26)$$

which means that the system (10) satisfies the $\mathcal{H}_\infty$ performance.

Theorem 2: Given positive scalars $\bar{\alpha}$, h, η_M, δ, μ, λ and matrix $\mathcal{R}$, the system (10) is MSES with $\mathcal{H}_\infty$ performance, if there exist positive symmetric matrices P, Q, R, Φ, $\mathbb{G}$ and matrices N, $\mathcal{S}$, the following conditions hold

$$\widetilde{\Theta} < 0 \quad (27)$$

where

$\widetilde{\Theta}=[\Theta_{ij}]_{7\times 7}$, $\Theta_{11}=Q+\mu P+C^TC-e^{-\mu h}M+2\mathcal{S}A$
$\Theta_{12}=e^{-\mu h}(M-N)+B\mathbb{G}C$, $\Theta_{13}=e^{-\mu h}N$
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$\Theta_{17}=-\mathcal{S}F$, $\Theta_{23}=-e^{-\mu h}(2M+2N)$
$\Theta_{22}=-e^{-\mu h}(M+2N)+\eta_M C^T\Phi C+\delta C^T\mathcal{R}^T\mathcal{R}C$
$\Theta_{24}=\lambda C^TR^TB^TS^T$, $\Theta_{25}=\eta_M C^T\Phi+\delta C^T\mathcal{R}^T\mathcal{R}$
$\Theta_{33}=-e^{-\mu h}(M+Q)$, $\Theta_{44}=-\lambda\mathcal{S}+h^2R$
$\Theta_{45}=\lambda B\mathbb{G}$, $\Theta_{46}=\bar{\alpha}\,\lambda B\mathbb{G}$, $\Theta_{46}=-\lambda\mathcal{S}F$
$\Theta_{55}=-\Phi+\eta_M\Phi+\delta C^T\mathcal{R}^T\mathcal{R}$, $\Theta_{66}=-\delta I$
$\Theta_{77}=-\gamma^2 I$

In this case, the controller gain is determined as $\mathrm{K} = (\mathrm{B}^T \mathcal{S}\mathrm{B})^{-1}\mathrm{B}^T \mathrm{B}\mathbb{G}$.

Proof: By employing Lemma 1 and the singular value decomposition of B, there exists matrix Y such that $\mathcal{S}B = BY$. In addition, defining $\mathbb{G} = YK$, we can get $\mathcal{S}BK = BYK = B\mathbb{G}$.

4. SIMULATION EXAMPLE

Let the nonlinear function as $\varphi(y(t_k h)) = 0.56y(t_k h) - \tanh(0.06y(t_k h))$. Other parameters are set as follows: $\bar{\alpha} = 0.5$, $\gamma = 0.3$, $\eta_M = 1.1$, $\delta = 0.1$, $\mu = 0.3$, $\lambda = 0.4$, $\omega(t) = 0.07e^{-2t}$, $h = 0.01$, $D = 0.9$, $M = 8$, $R = 0.03$, $\beta = 21, T_{ch} = 0.4, T_g = 0.2$.

By solving the inequalities in Theorem 2, we can obtain the controller gain $K = [-0.0458 \quad -0.3769]$.

Set the initial state of the system to be $x(0) = [0.5 \quad 0 \quad 0.1]^T$. The trajectories of system state are shown in Fig. 2. Figure 6 shows the release instants and intervals under the AET mechanism.

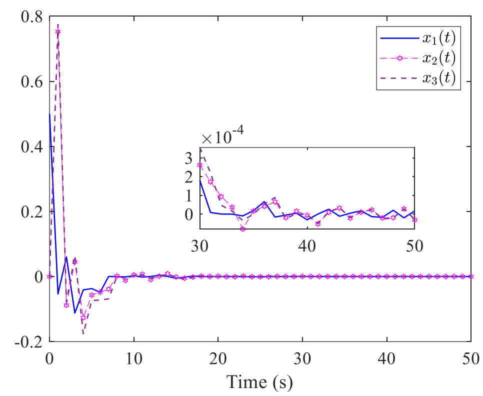

Fig. 2 System state

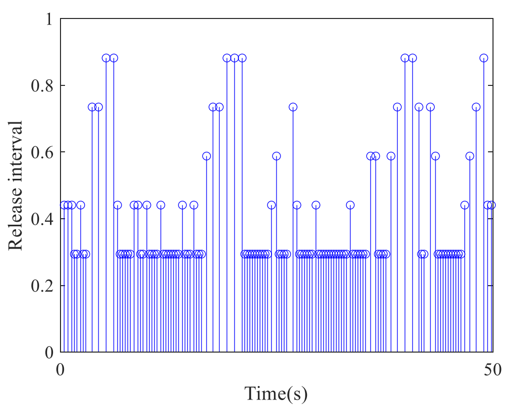

Fig. 3 The release instants and release intervals

5. CONCLUSION

In this paper, the event-based secure control problem for networked power system affected by FDI attack and AET mechanism has been addressed. An AET scheme is employed to predict the next triggered instant transfer in order to regulate the data transmission. Subsequently, by employing appropriate suitable matrix decoupling and separation methods, we have established a set of low conservative sufficient conditions to ensure the $\mathcal{H}_\infty$ performance of augmented system in MSES scenario. Finally, the feasibility of the proposed estimation scheme has been demonstrated in the simulation section.

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