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Resilient distributed economic dispatch of a cyber-power system under DoS attack

Key words: Economic dispatch; Denial of service (DoS) attack; Resilient event-triggered scheme; Distributed optimization

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Tendency and challenges

- Renewable energy generation has been widely studied at home and abroad in recent years to overcome the shortage of resources and environment pollution caused by conventional thermal generation (TG).

- As is well known, wind power generation (WG) and photovoltaic power generation (PG) have been applied widely because of their free availability and environmental friendliness. Nevertheless, WG and PG have strong randomness and uncertainty. Hence, the economic dispatch (ED) problem needs to be reformulated.

Motivation

- The distributed event-triggered scheme proposed in this study is resilient to data dropouts induced by DoS attack, and can effectively reduce the communication bandwidth consumption. The analytically explicit relationship between the proposed resilient triggered threshold and a general one is presented for the first time.
- An improved multi-agent consensus protocol is designed which eliminates the negative impacts of the centralized ED approaches despite the privacy preserving priorities of gradient information. The optimal active power output is also found by adopting a gradient descent algorithm, and a sufficient stability condition for the convergence to the equilibrium state is derived.

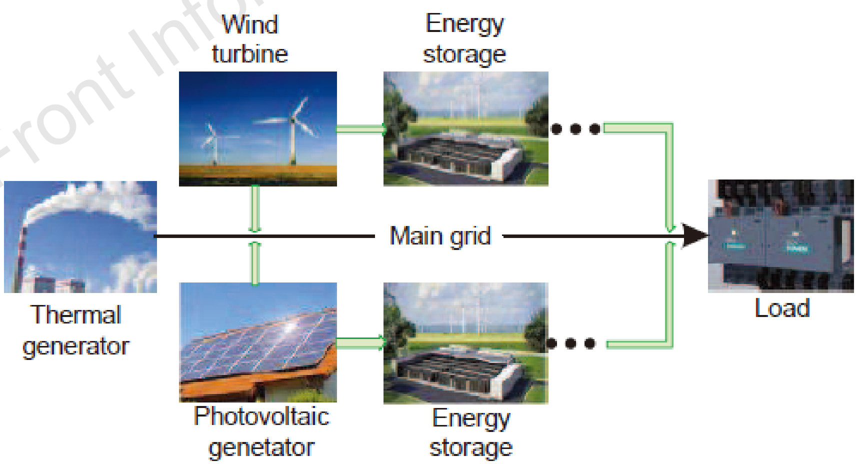


Fig. 1 Structure of the smart grid

Multi-agent optimization model

- To solve the distributed optimization problem, an improved dynamic multi-agent model is given.

$$\begin{cases} \dot{x}_i(t) = -\hat{a}\nabla c_i(x_i(t)) - \hat{b}u_i(t), \\ \dot{z}_i(t) = \hat{c}\sum_{j=1}^{N} a_{ij}(x_i(t) - x_j(t)), \end{cases} \tag{5}$$

where $\hat{a}$, $\hat{b}$, and $\hat{c}$ are positive constants which indicate the system parameters. $u_i(t) = \sum_{j\in N_i} a_{ij}(x_i(t) - x_j(t)) + z_i(t)$. $x_i(t)$ and $z_i(t)$ are the active power output and auxiliary state of agent *i* respectively, and N_i is the neighbor set of agent *i*. This improved multi-agent model can avoid the transmission of auxiliary state $z_i(t)$ and effectively reduce the communication cost.

Consensus closed-loop system

- It is known that communication interruption usually appears when that communication network is subjected to malicious DoS attack. Not all the triggered system states can be sent to the controller successfully. The system can be rewritten in a compact form.

$$
\begin{cases}
\dot{\boldsymbol{x}}(t) = -\hat{\boldsymbol{a}}\nabla \boldsymbol{c}(\boldsymbol{x}(t)) - (\boldsymbol{L} \otimes \hat{\boldsymbol{b}})(\boldsymbol{x}(t-d(t)) \\
\qquad\qquad + \boldsymbol{e}_k(t)) - \hat{\boldsymbol{b}}\boldsymbol{z}(t), \\
\dot{\boldsymbol{z}}(t) = \hat{\boldsymbol{c}}\boldsymbol{L}\boldsymbol{x}(t),
\end{cases}
$$

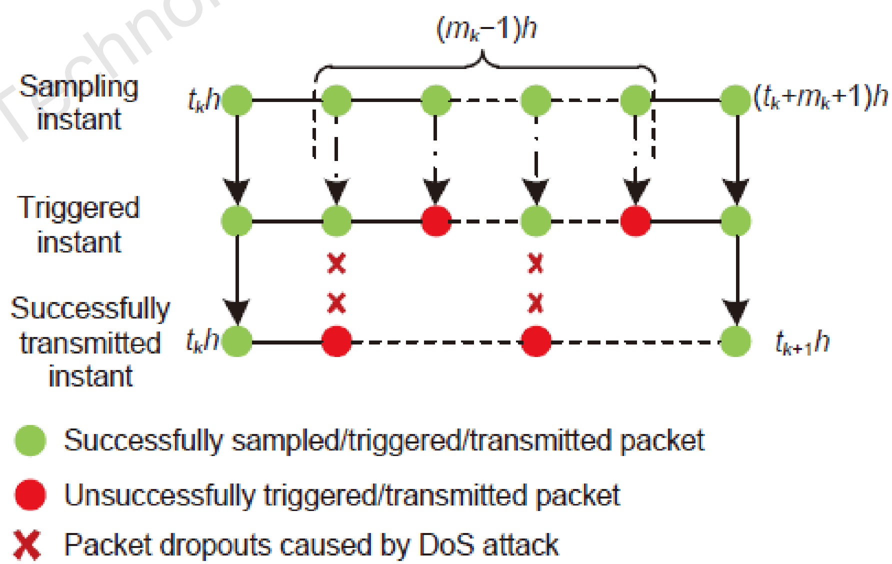


Fig. 2 Event-triggered sequence with DoS attack. m_k indicates the number of sampled packets in interval $[t_kh, t_{k+1}h)$

Stability analysis

- An augmented Lyapunov function can be constructed:

$$V(t) = (\boldsymbol{w}(t))^{\mathrm{T}}(\boldsymbol{P} \otimes \boldsymbol{I}_n)\boldsymbol{w}(t),$$

where $(\boldsymbol{w}(t))^{\mathrm{T}} = [(\tilde{\boldsymbol{x}}(t))^{\mathrm{T}} \ (\tilde{\boldsymbol{z}}(t))^{\mathrm{T}}]$, and $\boldsymbol{P}$ is the matrix to be defined.

- To simplify the statement, denote $\tilde{\boldsymbol{P}}_{ij} = \boldsymbol{P}_{ij} \otimes \boldsymbol{I}_n$, and define an augmented vector $\zeta(t)$ as follows:

$$\zeta(t) = \mathrm{col}\{\tilde{\boldsymbol{x}}(t),\ \nabla \boldsymbol{c}(\tilde{\boldsymbol{x}}(t)),\ \tilde{\boldsymbol{z}}(t)\}.$$

- Then $\dot{V}(t)$ can be written in the following compact form:

$$\begin{aligned}\dot{V}(t) =& \zeta^{\mathrm{T}}(t)[\mathrm{Sym}\{\boldsymbol{H}^{\mathrm{T}}\tilde{\boldsymbol{P}}_{11}\boldsymbol{e}_1 + \boldsymbol{H}^{\mathrm{T}}\tilde{\boldsymbol{P}}_{12}\boldsymbol{e}_3 \\ &+ \boldsymbol{H}_1^{\mathrm{T}}\tilde{\boldsymbol{P}}_{21}\boldsymbol{e}_1 + \boldsymbol{H}_1^{\mathrm{T}}\tilde{\boldsymbol{P}}_{22}\boldsymbol{e}_3\}]\zeta(t).\end{aligned}$$

Stability analysis (Cont'd)

- Hence, if the system has a feasible solution, we can conclude that $\dot{V}(t) < 0$, and the system is asymptotically stable. The residual system is asymptotically stable if and only if there exists a matrix ***P*** such that the following LMI holds:

$$\begin{aligned} &\mathrm{Sym}\{\boldsymbol{H}^{\mathrm{T}}\boldsymbol{P}_{11}e_1 + \boldsymbol{H}^{\mathrm{T}}\boldsymbol{P}_{12}e_3 \\ &+\boldsymbol{H}_1^{\mathrm{T}}\boldsymbol{P}_{21}e_1 + \boldsymbol{H}_1^{\mathrm{T}}\boldsymbol{P}_{22}e_3\} < 0, \end{aligned} \qquad (15)$$

where

$$0 < \boldsymbol{P} = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} \\ * & \boldsymbol{P}_{22} \end{bmatrix} \in \mathbb{R}^{(2Nn)\times(2Nn)}$$

$$\boldsymbol{H} = -\hat{a}e_2 - \hat{b}e_3$$

$$\boldsymbol{H}_1 = \hat{c}\boldsymbol{L}e_1$$

$$\mathrm{Sym}\{(\cdot)\} = (\cdot) + (\cdot)^{\mathrm{T}}$$

$$e_i = \begin{bmatrix} 0_{n\times[(i-1)n]} & \boldsymbol{I}_n & 0_{n\times[(3-i)n]} \end{bmatrix} \quad (i = 1, 2, 3)$$

Case study

- A comparison simulation is performed to verify the effectiveness of the proposed resilient triggered scheme. Suppose that the single-area power system consists of four TGs, three WGs, and three PGs.

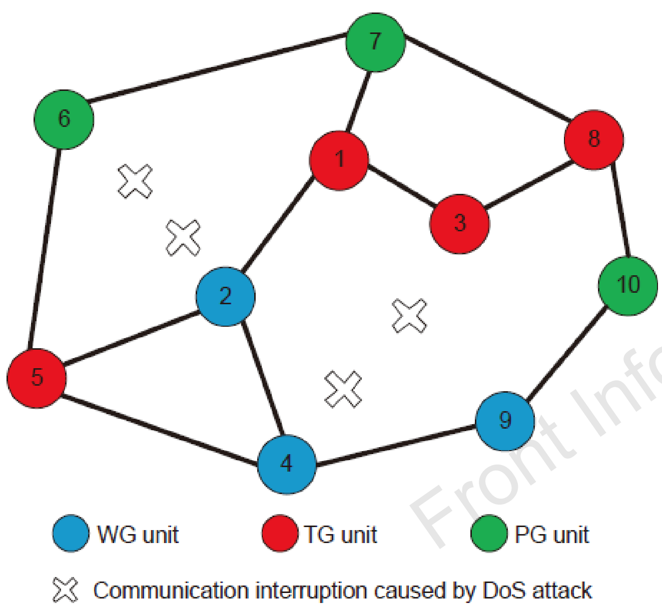


Fig. 3 Communication topograph with denial of service (DoS) attack. References to color refer to the online version of this figure

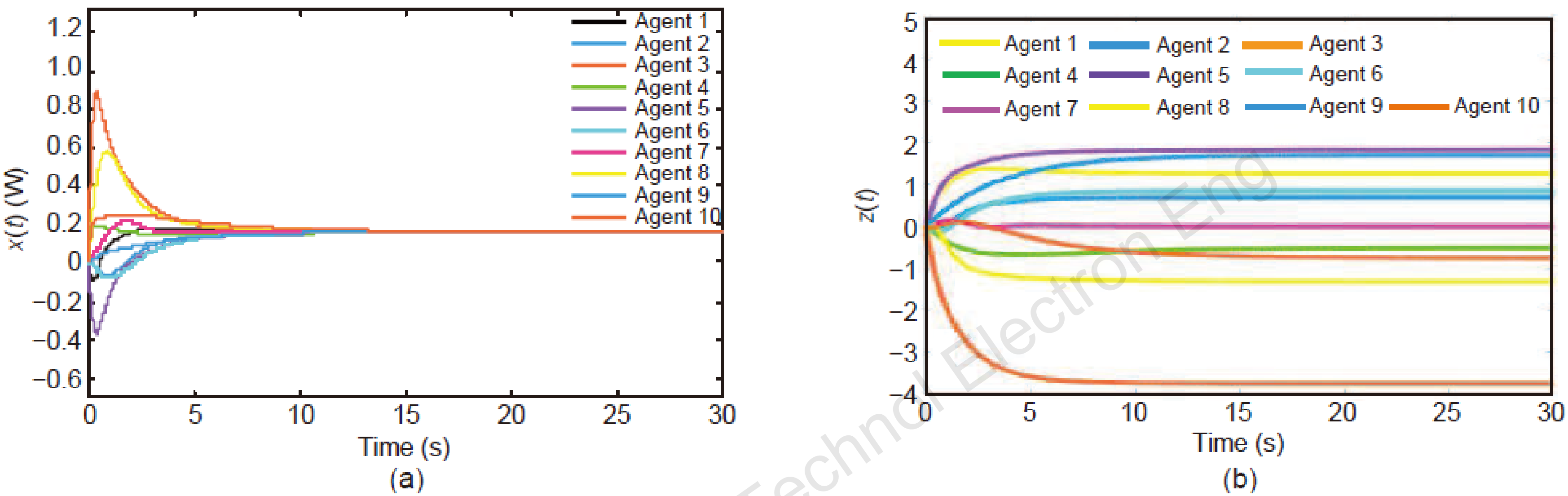
Table 1 Model parameters of thermal generation (TG)

i	α_i	β_i	γ_i	$\eta_{\mathrm{EPP}i}$	a_i	b_i	c_i
1	12	1.4	2	0.5	3	0.92	3
3	20	−10	5	0.4	1	−4	8
5	14	5	2	0.6	0.8	0	−9
8	5	−5	1.5	0.8	0.4	2	1

Table 2 Model parameters of wind power generation (WG, left) and photovoltaic power generation (PG, right)

i	$a_{\mathrm{w}i}$	$b_{\mathrm{w}i}$	$c_{\mathrm{w}i}$	i	$a_{\mathrm{p}i}$	$b_{\mathrm{p}i}$	$c_{\mathrm{p}i}$
2	2	0	0	6	2.4	0	0
4	1.5	−0.4	−0.6	7	1.2	−0.3	−0.8
9	8	0	0	10	6	−3	−2

Case study (Cont'd)



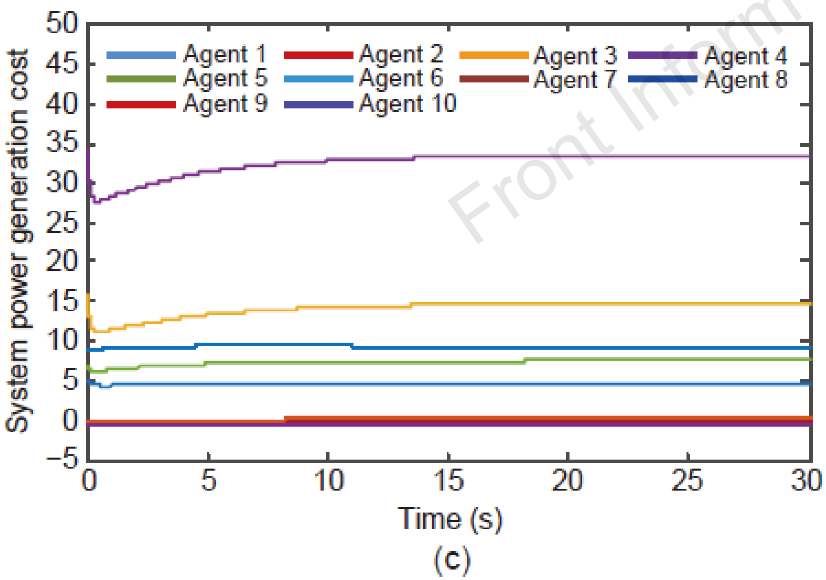
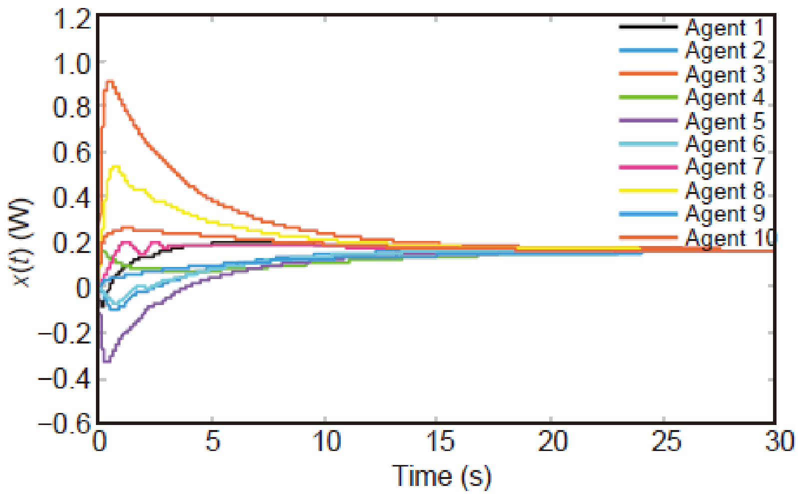
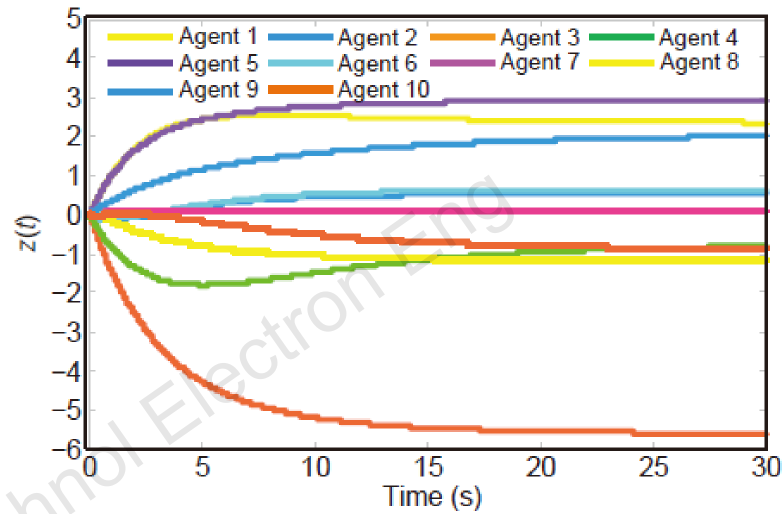


Fig. 4 Change trends of the multi-agent system state $x(t)$ (a), auxiliary state $z(t)$ (b), and system power generation cost (c) without DoS attack. References to color refer to the online version of this figure

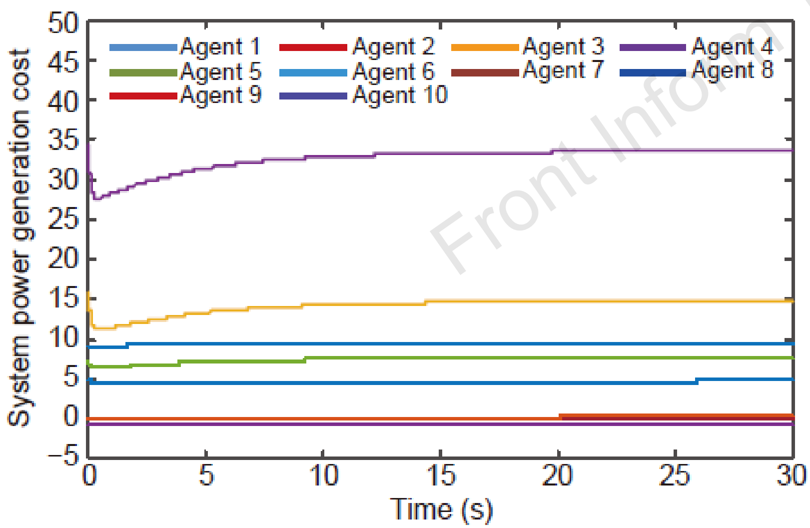
Case study (Cont'd)



(a)



(b)



(c)

Fig. 5 Change trends of the multi-agent system state $x(t)$ (a), auxiliary state $z(t)$ (b), and system power generation cost (c) with DoS attack. References to color refer to the online version of this figure

Conclusions

- In this paper, we are concerned mainly with the distributed economic dispatch optimization problem of a smart grid in the presence of malicious attack on the communication network.
- To reduce the communication bandwidth consumption and eliminate the effects caused by DoS, a distributed resilient event-triggered scheme has been proposed, and the explicit relationship between the resilient triggered threshold σ_{re} and a general one is established.
- A modified multi-agent model has been put forward which transforms the minimization problem into a consensus protocol design problem, and a sufficient condition for reaching the optimal state has been derived.
- Finally, the effectiveness of the proposed method is verified by simulations.

Feisheng YANG received the PhD degree in control theory and control engineering from Northeastern University (NEU), Shenyang, China, in 2013. He joined as an associate professor in Northwestern Polytechnical University in 2014. In 2015, he was a visiting associate professor in Department of Computer Science and Information Technology, La Trobe University, Australia. From 2016 to 2017, he was a visiting scholar in Department of Mechanical and Aerospace Engineering, University of California, San Diego, CA, USA. His research interests include time-delay systems and distributed parameter systems, networked control and power systems, control, privacy, and security for cyber-physical systems (CPS2), etc.

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