Analysis on Impact of Rumors on Electricity Market Operations with Volatile Renewables

Xiangyu Ma, Zhiyi Li, *Senior Member*, *IEEE*, and Huanhai Xin, *Member*, *IEEE*

***Abstract*—In recent years, rumors have been shown to have a significant impact on individual and societal activities. As renewables play an increasingly significant role in electricity markets, certain rumors may deviate the bidding behavior of market entities and eventually affect the performance of market operations. In this study, we attempt to reveal the general threats caused by rumors in the context of day-ahead electricity markets considering the integration of volatile renewables. First, we model the propagation of rumors in the societal system considering the weight of propagation resistance, which principally reflects the communication accessibility of market entities. Second, we develop an integrated two-layer network model to uncover the inherent coupling mechanism between market operations and rumor propagation. In particular, the role of electricity market operations on rumor propagation is characterized by changes in the truthfulness of rumors associated with electricity prices. The rumors, in turn, affect the bidding quantities of market entities in electricity market operations. Finally, numerical experiments are conducted on modified IEEE 6-bus and 118-bus systems. The results demonstrate the potential threats of rumors to electricity market operations with different penetration levels of renewables.**

***Index Terms*—Electricity market, integrated network modeling, renewables, rumor propagation.**

I. Introduction

THE development of electricity markets and integration of volatile renewables such as wind and solar energy are the two major reforms that all modern power systems have experienced. As it is common for electricity markets to guarantee a higher priority to dispatch renewables, the generation-side uncertainty and volatility resulting from an ever-increasing penetration of renewables may have a significant impact on the pricing of electricity services supplied to customers. Simultaneously, modern power systems are more closely coupled with societal systems, and such couplings further complicate power system operation. For example, the Indian government called on citizens to light candles to pray for the end of the COVID-19 pandemic, which caused considerable challenges to the Indian power system by creating an enormous load drop (about 32 GW) [1]. A comparable phenomenon occurs as an impact of the "Earth Hour" electricity saving action worldwide [2]. Additionally, lockdown policies against the COVID-19 pandemic have been proven to reshape electricity demand curves [3]. Such significant yet unusual disturbances from societal systems may cause risks for the electricity supply, particularly when volatile renewables play a substantial role in power system operation.

In addition to prevailing attacks such as false data injection [4], [5] and denial-of-service attacks launched at the cyber side of modern power systems, a wide spectrum of threats from the societal side deserve attention. Rumors are one of the most representative societal threats and have approximately coexisted with human society. By definition, a rumor is a piece of unverified information that may or may not be true, which is likely to propagate widely in society. With the development of social networking applications and new media, rumors tend to occur more frequently, propagate faster, and become easier to be trusted believe. The rumor propagation has already had a noticeable impact on the power system operation. For instance, at the end of year 2020, some provinces in China actually underwent the insufficiency of electricity and advocated the orderly electricity consumption [6]; however, rumors of "the electricity supply will be limited" initiated widespread and puzzled the public in other places that actually had no such concerns [7].

Some researchers have already examined the mutual influence of power and societal systems. Reference [8] proposed the concept of the cyber-physical-social system (CPSS) considering the factors of information and human activities to power systems. This sheds light on the necessity of a societal perspective in the rethinking of power system operations. Electricity markets are the key link between power systems and societal systems. When rumors related to electricity markets proliferate, market entities susceptible to those rumors would unintentionally challenge the market operation performance and eventually the security of the electricity supply. Inspired by the CPSS, rumors related to electricity markets can be defined as a generalized cyber-attack that actually changes the thinking patterns of operational de-

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X. Ma is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310063, China, and he is also with the Polytechnic Institute, Zhejiang University, Hangzhou 310063, China (e-mail: maxiangyu@zju.edu.cn).

Z. Li (corresponding author) is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310063, China, and he is also with the NGICS Platform, Zhejiang University, Hangzhou 310027, China (e-mail: zhiyi@zju.edu.cn).

H. Xin is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: xinhh@zju.edu.cn).

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cision-making and the associated bidding behaviors of market entities.

Meanwhile, with the implementation of Internet-of-Things technologies and advanced data analytics, customers are empowered to regulate their electricity usage patterns in response to the changes in electricity pricing. When allowed to participate in the day-ahead electricity market, the power consumption schedules of customers become more sensitive to the forecasted market-clearing prices. However, consumers commonly have a reduced capability to identify rumors compared to generation companies. Accordingly, customers are particularly susceptible to rumors, and are subject to the implications of rumors in determining their bidding behaviors. That is, the rumor propagation may reshape the performance of electricity market operation and leave consequences on both the power and societal systems, as shown in Fig. 1.

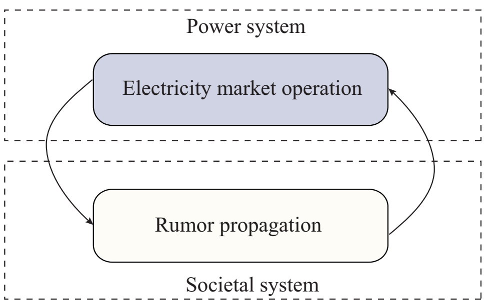

Fig. 1. Couplings between power and societal systems.

A high penetration of renewables entering the electricity market may affect pricing regularity, which provides the soil for breeding the rumors related to electricity markets. Rumors may utilize the uncertainty of electricity prices to mislead consumers' bidding behavior. Some studies have investigated rumor propagation in societal systems. Reference [9] developed a model of rumor propagation on social networks considering rumor mitigation in terms of negative energy. Reference [10] employed a compartment method to develop a dynamic model of rumor propagation on social networks. Reference [11] presented a model of rumor propagation considering the impacts of online and offline activities. Reference [12] considered the differences in individuals by state transition functions to develop a model of rumor propagation on social networks. However, these studies have not provided an insight into the rumors related to electricity markets. In addition, some studies have examined the impact of inherent power system characteristics on the bidding strategies of market entities. Reference [13] introduced an optimized bidding strategy model for distributed energy resources based on real-time electricity prices under the uncertainties of demand response and renewables-based generation. Reference [14] employed the paradigm of multiple agent systems to optimize bidding strategies for electric vehicle aggregators by considering various uncertainties. Reference [15] developed an agent-based model to explore the relationship between market design and bidding behaviors of market entities. Reference [16] proposed an optimization model for determining the bidding strategy of microgrid entities in distribution networks by considering the market competition together with the pricing and load uncertainty. Reference [17] developed a method based on supervised machine learning techniques to detect collusion among power generation companies. Reference [18] proposed a multi-agent deep deterministic strategy gradient method to approximate the Nash equilibrium in the bidding game of the day-ahead electricity market. Nevertheless, these studies have not thoroughly examined the role of external factors, e.g., rumors and other societal activities, in the context of electricity market operations.

To the best of our knowledge, there are few studies pertaining to the impact of rumor propagation on the operation of electricity markets. Provided that the threat of rumors needs to be urgently investigated in electricity markets with the increasing penetration of volatile renewables, the technical work in this study includes the following main contributions.

1) After classifying the potential sources and types of market-oriented rumors, the couplings between rumor propagation and market operations are investigated and analyzed.

2) An integrated and systematic approach is developed from a two-layer complex network perspective to quantify the impact of rumors on market operation performance.

3) The vulnerability of prevailing market-clearing mechanisms to rumors is revealed via a series of numerical simulations with varying penetration levels of renewables.

The rest of the paper is organized as follows. Section II states the types of rumors pertaining to electricity markets and presents the rumor propagation model in the context of electricity markets. Section III models the market-clearing by considering the rumor impacts from a two-layer network perspective, and proposes a mechanism for simulating the interaction between rumor propagation and electricity market operation. Section IV analyzes the results of numerical experiments. Finally, Section V draws the conclusions.

II. Types of Rumors Pertaining to Electricity Markets and Rumor Propagation Model

In this section, we characterize the types of rumors pertaining to the electricity markets and propose a rumor propagation model considering the operation of electricity markets.

A. Types of Rumors Pertaining to Electricity Markets

Rumors pertaining to electricity markets are classified as indirect or direct rumors based on their relevance to electricity market operations. Figure 2 shows that direct rumors refer to internal factors of electricity markets, including electricity prices, bidding information of market entities, and market operation mechanisms. For example, predictions regarding high or low electricity prices and false market regulation policies may directly influence the bidding strategies of market entities. The rumors indirectly related to electricity markets mean that their contents may interfere with the reference or basis for making bidding decisions of market entities. The relatively common content may be related to the conditions of the power system operation and equipment status. For example, news concerning the lack of coal supply, cyber-attacks, power shortages, and power equipment failures may affect the prediction of electricity prices by market entities. Moreover, the content of indirect rumors may not include any related information on the power system or electricity market. For instance, in the face of news related to public events and regulation policies, market entities may change their bidding behaviors to avoid potential losses.

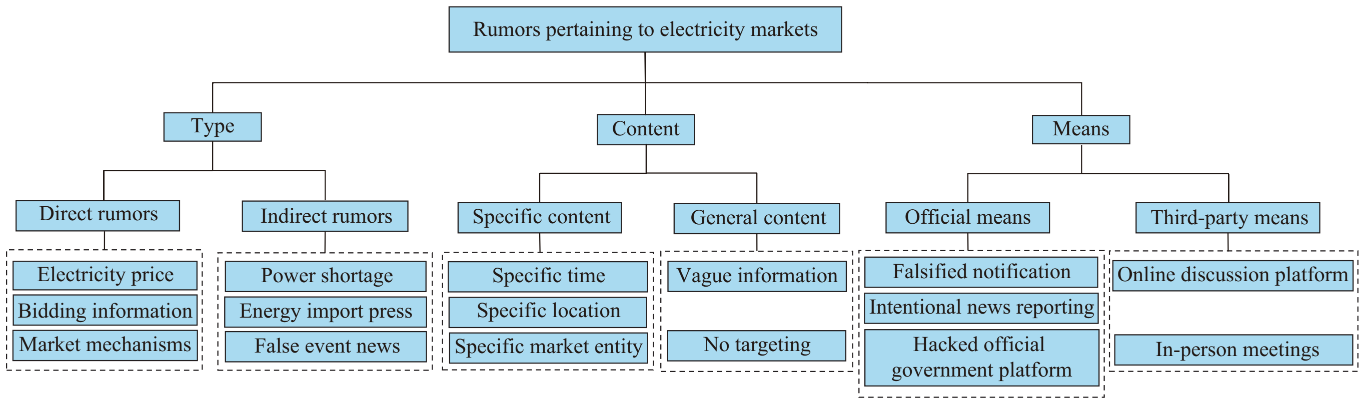

Fig. 2. Classification of rumors pertaining to electricity markets.

As for the content of rumors, they may contain specific content such as the specific time, specific location, and specific market entity. Rumors with specific time mean that there is clear time information in the contents. For example, "the electricity price will increase during 7-9 p.m. on 12$^{\text{th}}$ November", "the electricity price during the valley period will increase", and "the electricity price during the peak period will decrease". In contrast, rumors without any specific content are regarded as general rumors that contain vague information or the content is no targeting. For the propagation means, the source of rumors may be the official means, e.g., the hacked official government platform, falsified notification, and intentional news reporting, or a third-party means, e.g., online discussion platform or in-person meetings.

B. Two-layer Network Modeling of Electricity Markets

Considering the social and physical properties of electricity markets, the electricity market is modeled as a two-layer network, including the power system layer and the societal system layer, as shown in Fig. 3. For the power system layer, the structure is naturally a complex network, where each node denotes a bus, and each edge between nodes denotes a power delivery line.

The propagation of rumors between market entities is also modeled as a complex network for the societal system layer, which essentially reflects the relationship of information sharing between market entities. In detail, nodes in the network are the entities at the same location as the power system buses, implying that the nodes in the societal system layer have the same geographic properties as the buses in the power system layer. However, unlike power systems, information can flow efficiently on the Internet via social networking applications, e.g., WeChat, Twitter, and Facebook. Accordingly, even for nodes that are geographically distant and not connected by power lines, rumors can still propagate between them; therefore, it is likely to be an edge between each pair of nodes in the societal system layer.

Meanwhile, a high penetration of volatile renewables poses challenges to the secure operation of power systems and introduces significant uncertainty to electricity market management. Moreover, various types of rumors may cause frequent disturbances to the societal system layer and eventually pose risks to market operations. Market entities that believe in rumors may deliver false supply and demand information to other entities which change their bids simultaneously. For instance, if rumors concerning "electricity price will increase sharply" propagate in an area, the related market entities may reduce their bidding quantity, which further exacerbates the challenges to the operation of electricity markets under volatile renewables-based generation.

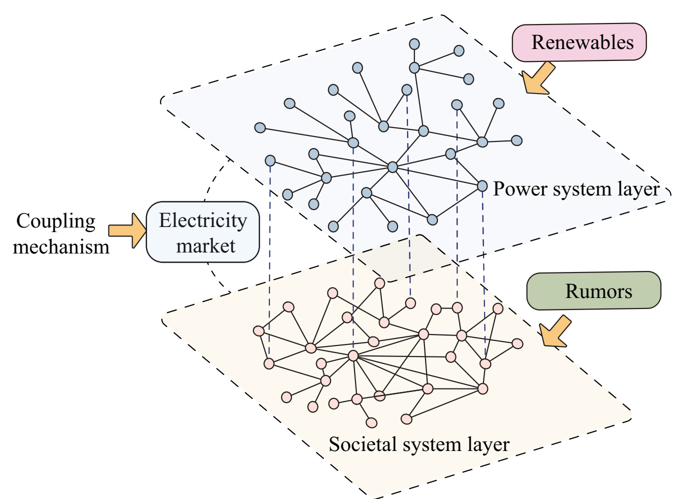

Fig. 3. Modeling of power and societal systems as a two-layer network.

C. Rumor Propagation Process Modeling

The SIS model was originally proposed to study the propagation of infectious diseases. In the SIS model, the nodes in the "S" state denote those who are susceptible to the infectious disease but have not been infected yet, and the nodes in the "I" state denote those who have already been infected with the disease. Moreover, those infected with infectious diseases (nodes in the "I" state) may return to susceptible people (nodes in the "S" state) after treatment, and vice versa. The traditional modeling of the rumor propagation process resembles the SIS model [19] - [22]. In the context of modeling rumors pertaining to electricity markets, nodes in the "S" state denote market entities that are likely to believe in rumors but have not done yet; the nodes in the "I" state denote market entities that have already believed in rumors and would potentially propagate rumors to other entities. In addition, the transition from "S" to "I" means a market entity turns to believe in a rumor, as influenced by other entities. In detail, when a node is in the "I" state, it has a certain possibility of propagating the rumor to others who originally doubt the rumor (nodes in the "S" state) and influence them to believe in the rumor. The possibility of such state transition for that is regarded as the propagation rate for the nodes in the "I" state. The transition from "I" to "S" means a market entity previously believed in a rumor but begins to doubt the same type of rumors. Moreover, the nodes in the "I" state still have a certain possibility to screen out the rumors and then recover to the "S" state. The possibility of such state transition is regarded as the recovery rate for nodes in the "I" state.

In the traditional SIS model, the propagation and recovery rates are assumed identical for all nodes and do not change with time. However, the possibility of individual market entities to believe in and propagate rumors is different and varies with the rumor propagation process. Accordingly, the possibility of believing in and doubting rumors should not be constant. Based on the traditional SIS model, we introduce electricity market-SIS (EM-SIS) as an integrated model of electricity market operations and rumor propagation. In particular, to better characterize the rumor propagation between market entities, we model the state changes of each node as follows.

For the k^{th} rumor occurrence, we assume a node is in the "I" state, and the rest of nodes are all in the "S" state. The transition of node states from "S" to "I" is simply denoted as $S \rightarrow I$. The possibility of this progress $p_{i,k}^{S \rightarrow I}$ is calculated as:

$$p_{i,k}^{S \rightarrow I} = 1 - \prod_{j \in I} (1 - \beta_{j,k} a_{i,j}) \quad \forall i \in S \tag{1}$$

where k is the occurrence number of rumors; I is the set of nodes that are in the "I" state; S is the set of nodes that are in the "S" state; $\beta_{j,k}$ is the rumor propagation rate of node j, which is in the "I" state; and $a_{i,j}$ is the element of the network adjacency matrix. If $a_{i,j} = 1$, then there is an edge between nodes i and j, and if $a_{i,j} = 0$, then there is no edge between nodes i and j. The transition of node states from "I" to "S" is simply denoted as $I \rightarrow S$, and the probability of this progress $p_{j,k}^{I \rightarrow S}$ is calculated as:

$$p_{j,k}^{I \rightarrow S} = \gamma_{j,k} \quad \forall j \in I \tag{2}$$

where $\gamma_{j,k}$ is the recovery rate of node j, which belongs to the "I" state.

We further consider the coupling of rumor propagation and electricity market operations. For each market entity, the probability of believing in a rumor is related to the truthfulness of rumors with the locational fact. Mathematically, for node j, the rumor propagation rate $\beta_{j,k}$ and recovery rate $\gamma_{j,k}$ are calculated as:

$$\beta_{j,k} = \eta_{j,k-1} \mu + \beta_{j,k-1} \quad -1 \le \eta_{j,k-1} \le 1, \forall j \in I \tag{3}$$

$$\gamma_{j,k} = -\eta_{j,k-1} \mu + \gamma_{j,k-1} \quad -1 \le \eta_{j,k-1} \le 1, \forall j \in I \tag{4}$$

where μ is a hyperparameter that measures the impact of the truthfulness of rumors on the propagation rate; $\beta_{j,k-1}$ and $\gamma_{j,k-1}$ are the propagation and recovery rates of node j at the time of last rumor occurrence, respectively; and $\eta_{j,k-1}$ is the truthfulness of last rumor, i. e., "high price", for node j, which is calculated as:

$$\eta_{j,k-1} = \begin{cases} 1 & \chi_{j,k-1} > 2\hat{\chi}, \forall j \in I \\ \dfrac{\chi_{j,k-1} - \hat{\chi}}{\hat{\chi}} & 0 < \chi_{j,k-1} \le 2\hat{\chi}, \forall j \in I \\ -1 & \chi_{j,k-1} \le 0, \forall j \in I \end{cases} \tag{5}$$

where $\chi_{j,k-1}$ is the locational marginal price at node j in the last occurrence; and $\hat{\chi}$ is the reference value of the electricity price level that is set to estimate whether the price is high or low so as to measure the trustfulness level of the "high price" rumors. The reference value can be set based on practical experience or investigation. Accordingly, $\eta_{j,k-1}$ takes a value in the range of $[-1,1]$, and the truthfulness level of rumors is limited when the electricity price is twice higher than the reference value. For a rumor of "high electricity prices across the system", if $\eta_{j,k-1} > 0$, the rumor is regarded by node j as a successful prediction and then believed in; if $\eta_{j,k-1} \le 0$, the rumor is regarded as fake and screened out. Although the trustfulness level of rumors depends on the locational fact, the content of rumors does not need to be false to have a considerable impact on the electricity market operation. In reality, the threat of rumors relates to the resulting sudden and simultaneous changes in the bidding behaviors of market entities.

Furthermore, the information sharing intensity between market entities is linked to their geographical locations. For instance, market entities have relatively less resistance to sharing information when they are geographically closer, whereas those that are geographically farther away have relatively more resistance to sharing information. Thus, we model a fully connected network with weighted edges to enrich the rumor propagation process. The weight of the edges between nodes i and j is denoted as the attenuation rate of rumors, as calculated by:

$$\omega_{i,j} = \frac{(\ell_{i,j} - \ell^{\min})\bar{\omega}}{\ell^{\max} - \ell^{\min}} \quad \forall i,j \in \Omega \tag{6}$$

where $\ell_{i,j}$ is the geographic distance between nodes i and j; $\ell^{\max}$ and $\ell^{\min}$ are the maximum and minimum values of the geographic distance set, respectively; Ω is the set of nodes; and $\bar{\omega}$ is the upper limit of the weight of edges. With a weighted network, the rumor propagation rate $\hat{p}_{i,k}^{S \rightarrow I}$ can be modified from (1) to (7), which indicates that $\hat{p}_{i,k}^{S \rightarrow I}$ can better reflect the diversity of the propagation resistance in the societal system layer.

$$\hat{p}_{i,k}^{S \rightarrow I} = 1 - \prod_{j \in I} [1 - (1 - \omega_{i,j}) \beta_{j,k} a_{i,j}] \quad \forall i \in S \tag{7}$$

III. Interactive Modeling of Rumor Propagation and Market Operation

In this section, we develop a market clearing model for day-ahead electricity market operations under the influence of rumors and illustrate the mechanism of interaction between rumor propagation and electricity market operation.

A. Electricity Market Operations Under Rumors

Inspired by the investigations presented in [23], [24], we develop a decision-making model for day-ahead electricity market operations considering the changes in bidding quantity owing to rumors. To simplify the modeling, several assumptions are made as follows: ① consumers have less capability to identify and ignore rumors than that of generation companies so that only market entities representing consumers will be sensitive to and influenced by rumors; ② conventional generation companies can submit both bidding prices and quantities, whereas consumers are price-takers that only submit bidding quantities; ③ renewables-based generation companies only include wind farms that also act as price-takers; ④ the impact of rumors on electricity market operation is reflected by the changes in the bidding quantities of market entities; ⑤ every node is exposed to rumors, but whether a node in the "S" state believes in the rumors is influenced by a neighboring node in the "I" state. Therefore, adjustable loads are considered to simulate the changes in the bidding quantities caused by rumors. The k^{th} occurrence of rumors $\hat{\delta}_{d,k}$ is referred to as the incremental rate of bidding quantity of the consumer d owing to rumors, which is calculated as:

$$\hat{\delta}_{d,k}=\begin{cases}\beta_{j,k}\sigma & \forall d\in j, \forall j\in I\\ 0 & \forall d\notin j, \forall j\in I\end{cases} \tag{8}$$

where σ is a hyperparameter that reflects the relationship between the propagation rate and the reaction of consumers' behaviors to rumors; and $d\in j$ and $d\notin j$ represent that consumer d is at and not at node j, respectively. It is reasonable that the bidding decisions made by consumers who believe in and propagate rumors with a higher probability are more consistent with the rumor content.

For the detailed setting of σ in (8), if the rumor is related to "high price," then the value of σ is in the range of [−1, 0], i.e., the consumer will decrease the bidding quantity; if the rumor is related to "low price", then the value of σ is in the range of [0, 1], i.e., the consumer will increase the bidding quantity. A larger absolute value of σ represents a more radical reaction of consumers as a response to believing in the rumor. For example, if a rumor mentions "electricity price will increase sharply", σ is set as −0.1, the propagation rate is 0.6, and the original bidding quantity is 10 MW. The actual bidding quantity is calculated as $10+10\times0.6\times(-0.1)=9.4$ MW. Thus, the bidding quantity of consumer d is reduced by 6% as a result of the rumor.

Following the assumptions, the goal of electricity market operation is to minimize operational costs [25], [26], as described by:

$$\min\sum_{g}\sum_{t}C_g(P_{g,t}) \tag{9}$$

where $C_g(\cdot)$ is a function that quantifies the cost of dispatching thermal units g at time t; and $P_{g,t}$ is the generation amount of thermal unit g at time t.

The system-wide power balance constraint is as follows:

$$\sum_{g}P_{g,t}+\sum_{w}P_{w,t}=\sum_{d}\hat{D}_{d,t}:(\lambda_t)\quad \forall t \tag{10}$$

where λ_t is the dual variable of this constraint at time t; $P_{w,t}$ is the committed generation amount of wind farm w; and $\hat{D}_{d,t}$ is the bidding quantity of consumer d at time t, which is calculated as:

$$\hat{D}_{d,t}=\begin{cases}L_{d,t}+L_{d,t}\hat{\delta}_{d,t} & \forall d, \forall t\in T\\ L_{d,t} & \forall d, \forall t\notin T\end{cases} \tag{11}$$

where T is the set of specific time periods; and $L_{d,t}$ is the original power demand, i.e., the bidding quantity without the influence of rumors, of consumer d at time t.

The generation range of thermal units is restricted as:

$$\underline{P}_g\le P_{g,t}\le \overline{P}_g\quad \forall g, \forall t \tag{12}$$

where $\overline{P}_g$ and $\underline{P}_g$ are the maximum and minimum outputs of thermal unit g, respectively. In addition, the limitation of the wind generation amount is determined as:

$$0\le P_{w,t}\le \hat{P}_{w,t}\quad \forall w, \forall t \tag{13}$$

where $\hat{P}_{w,t}$ is the predicted generation of wind farm w at time t.

Thermal units are also subject to technical limitations on the ramping rates as follows:

$$P_{g,t+1}-P_{g,t}\le \overline{\xi}_g\quad \forall g, \forall t \tag{14}$$

$$P_{g,t}-P_{g,t+1}\le \underline{\xi}_g\quad \forall g, \forall t \tag{15}$$

where $\overline{\xi}_g$ and $\underline{\xi}_g$ are the maximum values of the upward and downward ramping rates of thermal unit g, respectively.

The transmission capacity of power lines is restricted by:

$$s_{l,i}\left(\sum_{g\in i}P_{g,t}+\sum_{w\in i}P_{w,t}-\sum_{d\in i}\hat{D}_{d,t}\right)\le \Gamma_l:(\lambda_{l,t}^{+})\quad \forall l, \forall t \tag{16}$$

$$-s_{l,i}\left(\sum_{g\in i}P_{g,t}+\sum_{w\in i}P_{w,t}-\sum_{d\in i}\hat{D}_{d,t}\right)\le \Gamma_l:(\lambda_{l,t}^{-})\quad \forall l, \forall t \tag{17}$$

where $\lambda_{l,t}^{+}$ and $\lambda_{l,t}^{-}$ are the dual variables of the corresponding constraints; Γ_l is the maximum transmission capacity of line l; $s_{l,i}$ is the shift factor of bus i to line l; $g\in i$ means that thermal unit g is located at bus i; $w\in i$ means that the wind farm w is at bus i; and $d\in i$ means that the consumer d is at bus i.

Moreover, to guarantee that the power system has sufficient capacity to tolerate uncertain fluctuations caused by renewables-based generation units and loads, system-wide reserve rates are restricted by (18) and (19), which can be further linearized into (20) and (21).

$$\sum_{g}\min\{\overline{P}_g-P_{g,t},\overline{\xi}_g\}\ge \overline{R}_t\quad \forall t \tag{18}$$

$$\sum_{g}\min\{P_{g,t}-\underline{P}_g,\underline{\xi}_g\}\ge \underline{R}_t\quad \forall t \tag{19}$$

$$\begin{cases}\sum_{g}\overline{\Upsilon}_{g,t}\ge \overline{R}_t & \forall t\\ \overline{P}_g-P_{g,t}\ge \overline{\Upsilon}_{g,t} & \forall g, \forall t\\ \overline{\xi}_g\ge \overline{\Upsilon}_{g,t} & \forall g, \forall t\end{cases} \tag{20}$$

$$\begin{cases} \sum_{g} \underline{\varUpsilon}_{g,t} \geq \underline{R}_t & \forall t \\ P_{g,t} - \underline{P}_g \geq \underline{\varUpsilon}_{g,t} & \forall g, \forall t \\ \underline{\xi}_g \geq \underline{\varUpsilon}_{g,t} & \forall g, \forall t \end{cases} \tag{21}$$

where $\overline{\varUpsilon}_{g,t}$ and $\underline{\varUpsilon}_{g,t}$ are the auxiliary variables that denote the upward and downward spinning reserve capacities of thermal unit g at time t, respectively; and $\overline{R}_t$ and $\underline{R}_t$ are the required upward and downward spinning reserves across the power system, respectively.

After solving the proposed optimization model (9)-(17), (20), and (21), we can obtain the locational marginal price $LMP_{i,t}$ for bus i at time t as:

$$LMP_{i,t} = \lambda_t - \sum_{l} s_{l,i} (\lambda_{l,t}^{+} - \lambda_{l,t}^{-}) \quad \forall i, \forall t \tag{22}$$

B. Interactions Between Rumors and Electricity Markets

We present a simple example to better illustrate the rumor propagation process, as shown in Fig. 4.

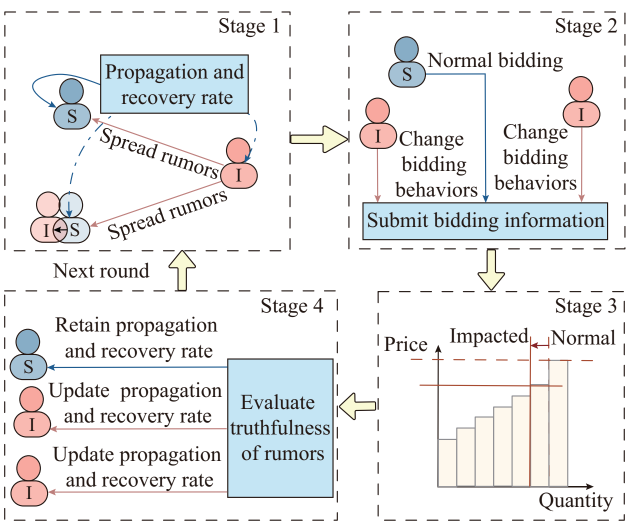

Fig. 4. Illustration of interactions between rumors and electricity markets.

Herein, we suppose three market entities exist in the system. Initially, the rumor of "electricity prices will increase sharply" propagates in the market, and two out of three market entities eventually believe in the rumor, as shown in stage 1 in Fig. 4. Correspondingly, the bidding behaviors of two market entities in the "I" state are influenced by the rumor, for example, bidding a reduced quantity of electricity consumption compared to normal circumstances, as shown in the stage 2 in Fig. 4. As a result of the misled bidding behaviors, the market operation is actually affected by market-clearing prices deviating from normal situation, as shown in the stage 3 in Fig. 4. Considering the locational factors, the implications of that rumor vary with market entities that may have different clearing prices. If the clearing results show that high electricity prices do occur in certain locations, the associated nodes in the "I" state (market entities) increase the propagation rate, reduce the recovery rate, and tend to believe in such rumor in the next round; otherwise, the associated nodes in the "I" state will reduce the propagation rate and increase the recovery rate in the next round, as shown in the stage 4 in Fig. 4. Since most rumors contain false information, all market entities would eventually ignore and avoid the implications of the rumors of the same type as they unfold repeatedly.

In addition to the locational/spatial coupling of rumor propagation and electricity market clearing, we perform a time-domain simulation for a series of similar rumors that occur in sequence, i.e., the temporal evolution of market entities' reactions to rumors. In particular, we perform a complete round of market-clearing simulation based on the eventual distribution of the nodes in the "I" state related to a certain rumor (instead of the detailed propagation dynamics of that rumor). The simulation steps for a series of similar types of rumors occurring in sequence are shown in Fig. 5, where N is the total number of nodes; and k_{max} is the maximum iteration number that curbs the total occurrence times of the rumors.

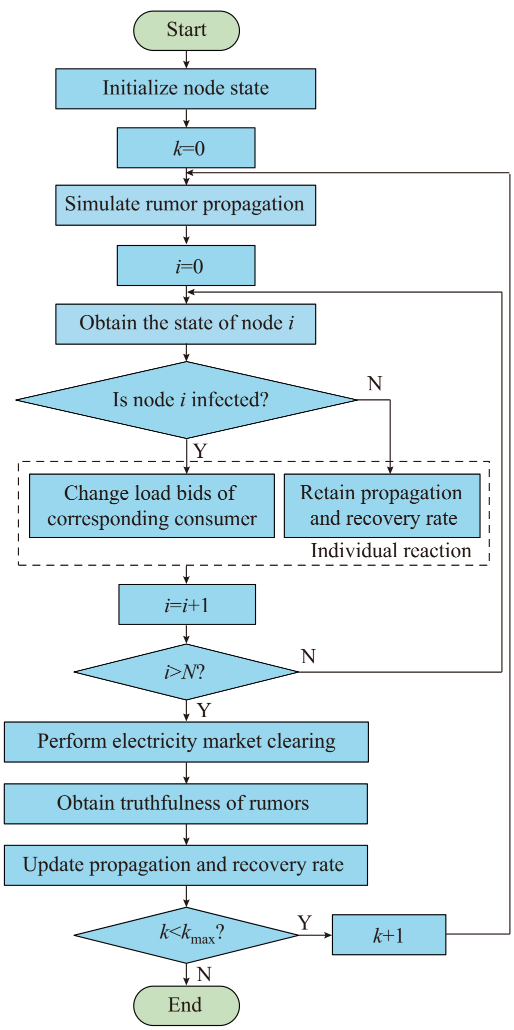

Fig. 5. Flowchart of modeling of rumor propagation in electricity markets.

In addition, only market entities in the "I" state concern about the truthfulness of rumors, and those who are in the "S" state do not pay attention to the deviation of rumors with facts. Accordingly, the changes of rumor propagation and recovery rates are only associated with nodes in the “I” state. Based on these characteristics, we construct a memory mechanism, in which nodes can memorize the previous values of propagation and recovery rates. For example, although a node in the “S” state would not be directly affected by rumors, it still retains the previous propagation rate to propagate rumors once it suddenly believes in rumors again, i.e., turns to a node in the “I” state.

IV. Numerical Experiments

In this section, we use two representative IEEE test systems [27] of different scales to demonstrate the coupling effects of rumor propagation and electricity market operations. Suppose that a series of rumors propagate in sequence with a specific content of “there will be electrical equipment failures between 7 a.m. and 11 a.m., which may cause high electricity prices”. The first case is conducted on the modified IEEE 6-bus system to particularly illustrate the mechanism of rumor propagation considering the result of electricity market clearing, and the second case is conducted on the modified IEEE 118-bus system to further demonstrate the interactions between rumor propagation and electricity market operation at different wind penetration levels. Numerical experiments are performed using the Python 3.7 (together with Gurobi and Networkx) on a desktop computer with an Intel Core(TM) i5-9400F 2.90 GHz CPU. Owing to the lack of actual bidding data, the bidding price function of each thermal unit is simplified to a quadratic cost function.

A. IEEE 6-bus System

The modified IEEE 6-bus system is illustrated in Fig. 6. The total capacity of installed thermal units is 390 MW, and a wind farm with a capacity of 39 MW is located on the 4th bus. One hundred scenarios are simulated when the wind power generation and load in each scenario are randomly sampled from 30 historical wind power generation curves and 50 load curves. The wind power generation is assumed 15% of the actual measured generation of Elia-connected onshore wind farms from January 1 to April 9, 2020 [28]. The load is 0.23 times the actual total load in Latvia from January 1 to February 19, 2020 [29]. We set geographic coordinates for each bus, and the rumor propagation network is constructed based on the geographic locations of those buses (colored in blue). The maximum attenuation rate is set to be 0.9. As shown in Fig. 6, each node denotes a market entity with the same geographic location as the power system bus. The edges between different nodes denote social connections. Darker blue color indicates lower resistance to rumor propagation, and lighter blue color indicates higher resistance to rumor propagation.

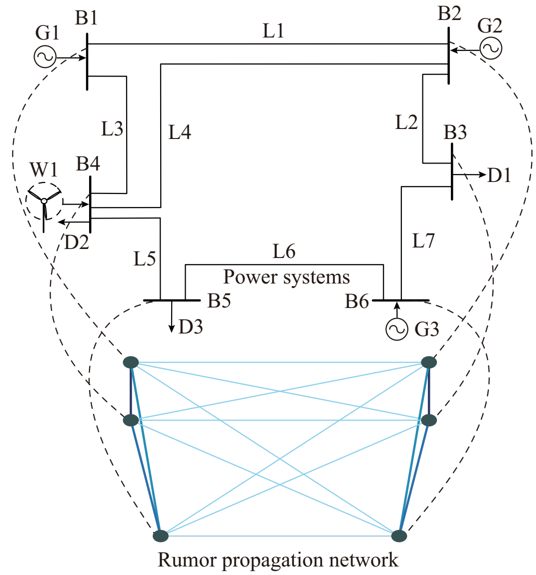

Fig. 6. Modified IEEE 6-bus system and coupled rumor propagation network.

To observe the impact of the market-clearing price on the rumor propagation related to electricity market, we conduct a set of controlled experiments with and without consideration of the electricity price effects. The initial values of propagation and recovery rates are set to be 0.3 and 0.1, respectively. μ is set to be 0.1, σ is set to be -0.1, and $\hat{\chi}$ is set to be 17.51 \$/MW.

Figure 7(a) indicates that the number of in the “I” state nodes is dominant in the simulations when the propagation and recovery rates are constant. As shown in Fig. 7(b), a relatively pronounced oscillation in the rumor propagation occurs considering the impact of electricity price on the truthfulness of rumors, which reveals that electricity market operation can affect the rumor propagation. Compared with Fig. 8(a), (b), and (c), we can find the diversity of propagation and recovery rates of market entities as well as the impact of electricity market operation on rumor propagation, where the red lines with different shades indicate the propagation rates of different market entities, and the blue lines with different shades denote the recovery rates of different market entities.

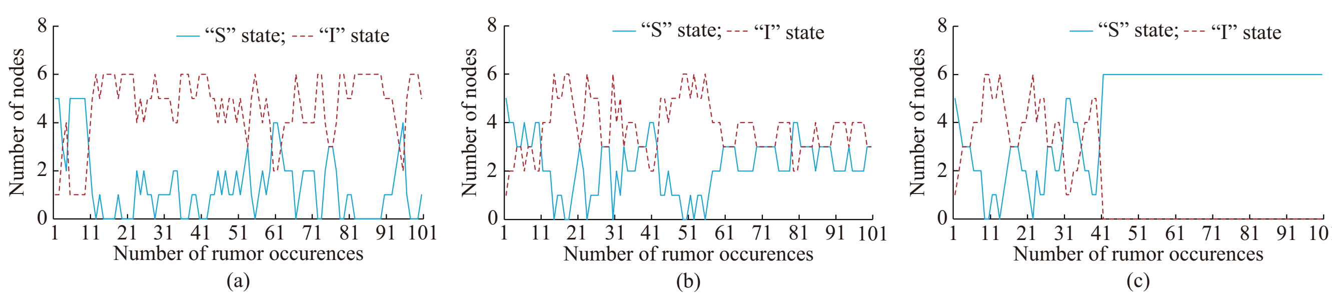

Fig. 7. Evolving process of nodes in “S” and “I” states. (a) Without consideration of truthfulness. (b) Only considering truthfulness (c) Considering both truthfulness and change of bidding behaviors.

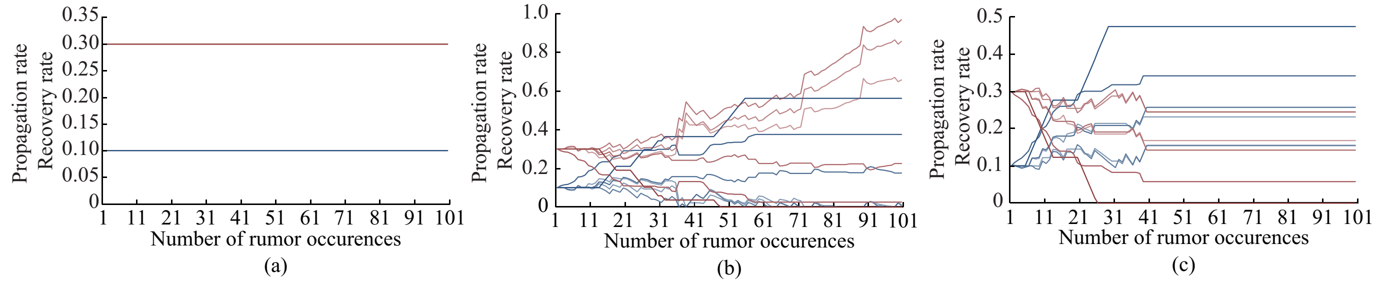

Fig. 8. Evolving process of propagation and recovery rates of nodes. (a) Without consideration of truthfulness. (b) Only considering truthfulness. (c) Considering both truthfulness and change of bidding behaviors.

To observe the indirect impact of bidding behaviors on the propagation of relevant rumors, we conduct a set of controlled experiments with and without consideration of the impact of the bidding behaviors as responses to rumors, respectively.

As shown in Fig. 7(c), when changes in the bidding behaviors are considered, the rumor propagation disappears naturally without any intervention, which is regarded as the self-limitation of rumors. Provided the impact of rumors on electricity markets, the bidding behaviors of consumers driven by rumors will first affect market-clearing prices. Consecutively, the influenced prices change the truthfulness of rumors related to "high price", which means changes in the bidding behaviors of consumers indirectly influence the rumor propagation; thus, the interaction between rumors and electricity markets forms a negative feedback in general.

B. IEEE 118-bus System

To observe the interaction between rumor propagation and electricity market operation in a larger and more complicated system, we implement numerical simulations in a modified IEEE 118-bus system. The total installed capacity of wind power generation is 1463 MW, where each wind farm with a capacity of 209 MW is located on buses 3, 6, 12, 37, 56, 72, and 112. The initial values of the propagation and recovery rates for all nodes are set to be 0.3 and 0.1, respectively. μ and σ are set to be 0.2 and -0.1, respectively. One hundred scenarios are considered in which wind power generation and loads are randomly sampled from 100 wind power generation curves and 100 load curves. The load curves are 1.5 times the actual total load of SE4 which is one of the bidding areas in Sweden from January 1 to April 9, 2020. The realistic generation amounts of Elia-connected onshore wind farms from January 1 to April 9, 2020 are doubled to form the wind power generation curves, which are used as the baseline levels of wind power generation. To observe the impact of different penetrations of renewables-based generation on electricity market, we set three scale factors, $\rho=1.0$, $\rho=1.5$, and $\rho=2.0$, which are 1.0, 1.5, and 2.0 times the base wind power generation, respectively. As shown in Fig. 9, the rumor propagation network of the IEEE 118-bus system is similar to that of the IEEE 6-bus system, in which the redder the color of the edge is, the higher the resistance to rumor propagation is, and the bluer the color of the edge is, the lower the resistance to rumor propagation is.

Figure 10 shows the total standard deviations of LMP between 7-11 a.m. with different scales of wind power generation for 100 simulations. The standard deviation of LMP gradually increases as the penetration of renewables increases; thus, the LMP of electricity markets with a high penetration level of renewables may be more diverse than that of electricity markets with a low penetration level of renewables. The diversity and uncertainty of prices provide an opportunity for rumor propagation. To evaluate the impact of rumor propagation on the electricity market with different penetration levels of renewables, we perform 100 simulations of rumor propagation and electricity price clearing under the cases of $\rho=1.0$, $\rho=1.5$, and $\rho=2.0$. Moreover, to evaluate the level of electricity prices for different buses based on (5), a reference value is set as follows. First, calculate the average electricity price between 7-11 a.m. for each market-clearing simulation without consideration of the rumors while assuming that all wind power generation and load data are the same as the rumor propagation situation. Second, calculate the median value of electricity prices in the 100 simulations, which is regarded as a reference value to distinguish between the high and low electricity prices. Third, set different reference electricity prices for the three cases with $\rho=1.0$, $\rho=1.5$, and $\rho=2.0$, which are 17.27, 16.71, and 15.95 \$/MW, respectively. Since renewables-based generation companies only act as price-takers in market clearing, the electricity price decreases as ρ increases.

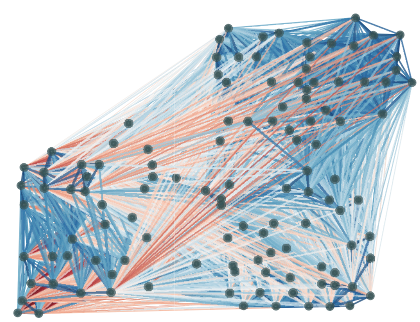

Fig. 9. Rumor propagation network for IEEE 118-bus system.

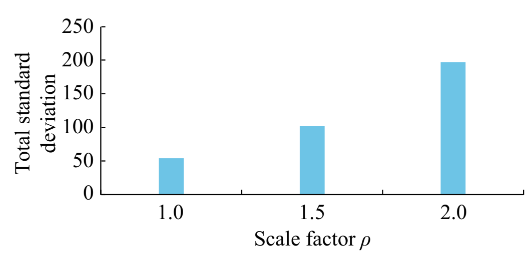

Fig. 10. Total standard deviations of average LMP with different scales of wind power generation.

Figure 11 illustrates the evolving process of nodes in the “I” and “S” states in the three cases. Figure 12 presents the evolving process of propagation and recovery rates of nodes in the three cases, whereas the red and blue lines with different shades indicate the propagation and recovery rates of different market entities, respectively. The propagation of “high price” rumors related to electricity markets in the case of $\rho = 1.5$ exhibits more pronounced self-limitation than that of the case of $\rho = 1.0$, whereas the evolutionary process of propagation and recovery rates at different nodes in the case of $\rho = 1.5$ is moderately more diverse than that of the case of $\rho = 1.0$. Additionally, although the number of nodes in the “I” state decreases rapidly in the early stages of rumor propagation under the case of $\rho = 2.0$ compared with that in the cases of $\rho = 1.0$ and $\rho = 1.5$, the number of nodes in the “I” state declines relatively slowly in the later stages of rumor propagation, implying that rumors may have a more lasting impact on the electricity market operation.

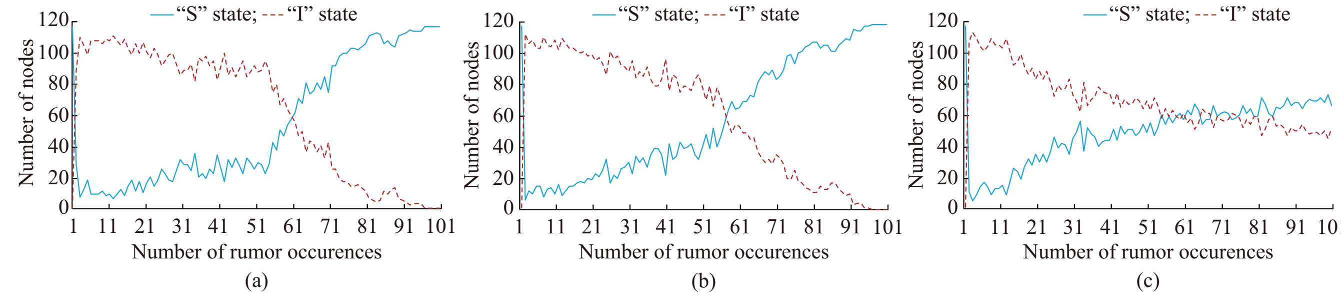

Fig. 11. Evolving process of nodes in “S” and “I” states in three cases. (a) ρ=1.0. (b) ρ=1.5. (c) ρ=2.0.

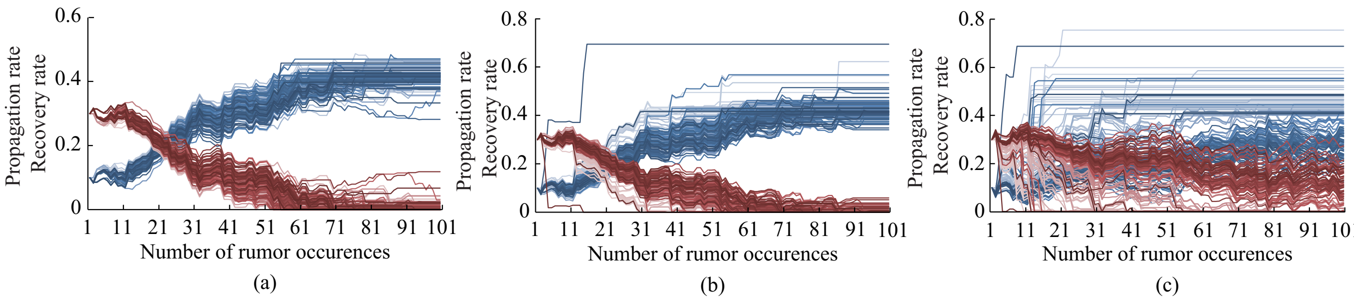

Fig. 12. Evolving process of propagation and recovery rates of nodes in three cases. (a) ρ=1.0. (b) ρ=1.5. (c) ρ=2.0.

To quantify the impact of rumor propagation on the electricity market, we count the total changes in electricity prices, bidding quantities of consumers, and wind power curtailments of all nodes in each market-clearing round with and without rumor propagation, respectively. The market-clearing results without the impact of rumors are regarded as reference values; thus, the threat of rumors can be reflected by comparing the market clearing results with the reference values in the normal case.

As shown in Figs. 13(a) and 14(a), rumors have a considerable effect on electricity prices. The electricity price significantly drops in the early stages of rumor propagation. In detail, the case with $\rho = 2.0$ experiences the largest decline, followed by the case with $\rho = 1.5$. For the total electricity price decline obtained from 100 simulations, the effect of rumors on electricity prices gradually increases as ρ increases. As shown in Figs. 13(b) and 14(b), a significant drop in the bidding quantities exists at the beginning of rumor propagation, which may cause extensive losses for the electricity market, such as loss of revenue for generation companies and additional costs for consumers to adjust their own electricity demands. The largest drop of the total bidding quantity is observed in the case of $\rho = 2.0$, whereas the results of the cases with $\rho = 1.0$ and $\rho = 1.5$ are relatively close.

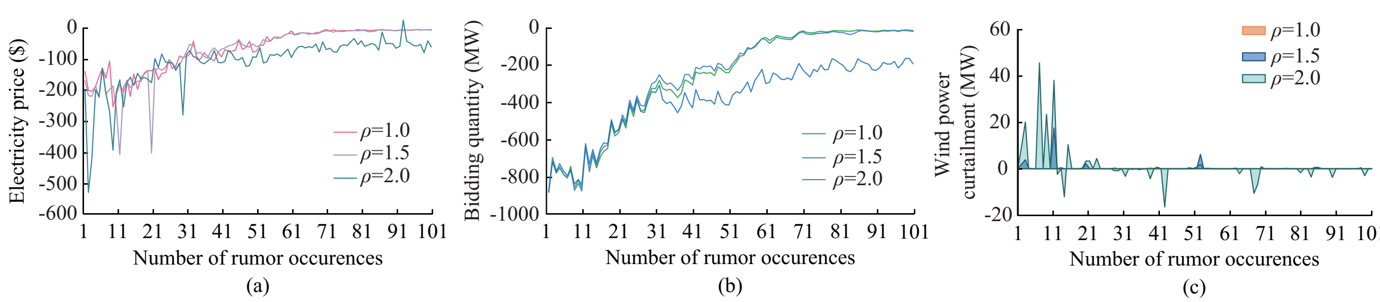

Fig. 13. Evolving process of impacts of rumor propagation on changes of electricity prices, bidding quantities, and wind power curtailments of all nodes. (a) Electricity prices. (b) Bidding quantities. (c) Wind power curtailments.

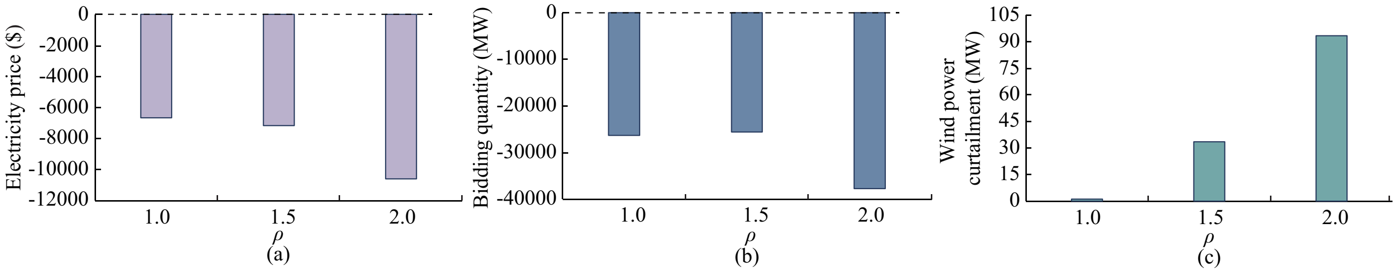

Fig. 14. Total changes of electricity prices, bidding quantities, and wind power curtailments of all nodes due to rumor propagation. (a) Electricity prices. (b) Bidding quantities. (c) Wind power curtailments.

As shown in Figs. 13(c) and 14(c), different levels of additional wind power curtailment exist owing to rumor propagation in electricity markets with different scales of wind power generation. At the early stages of the rumor propagation, the extra wind power curtailment in the case of $\rho=2.0$ is significantly higher than that in the other two cases, and the case of $\rho=1.5$ also exhibits significant extra wind power curtailment, while the case of $\rho=1.0$ is less affected. Furthermore, for the case of $\rho=1.5$, despite the propagation of rumors is similar to the case of $\rho=1.0$, the total extra wind power curtailment still increases significantly relative to the case of $\rho=1.0$ in 100 simulations. It is worth pointing out that for $\rho=2.0$, some of the rumors occasionally cause a reduction in wind power curtailment, but the total wind power curtailment remains significantly above the reference value. In summary, the above results imply that for electricity market with high wind power penetration level, rumors may lead to serious wind power curtailment.

Furthermore, we perform numerical experiments to explore how countermeasures mitigating rumor propagation influence the impact of rumors on electricity markets. Assume that all market entities are trained to improve their ability to identify rumors, which corresponds to an increase in the recovery rate and a decrease in the propagation rate in the EM-SIS model. In the case study of the IEEE 118-bus system, we select the case of $\rho=1.5$ and adjust the initial propagation and recovery rates of all nodes to 0.15 and 0.12, respectively, and perform 100 simulations. Figure 15 illustrates the impacts of countermeasures on the number of nodes in the "I" and "S" states. As shown in Fig. 15, the implemented countermeasures can help significantly curb the rumor propagation. Figure 16(a) and (b) reveals that the implemented countermeasures can reduce the wind power curtailment caused by rumors during electricity market operation.

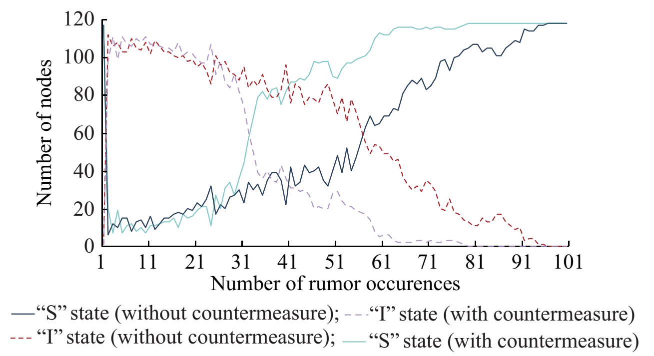

Fig. 15. Evolving process of impacts of countermeasures on number of nodes in "S" and "I" states.

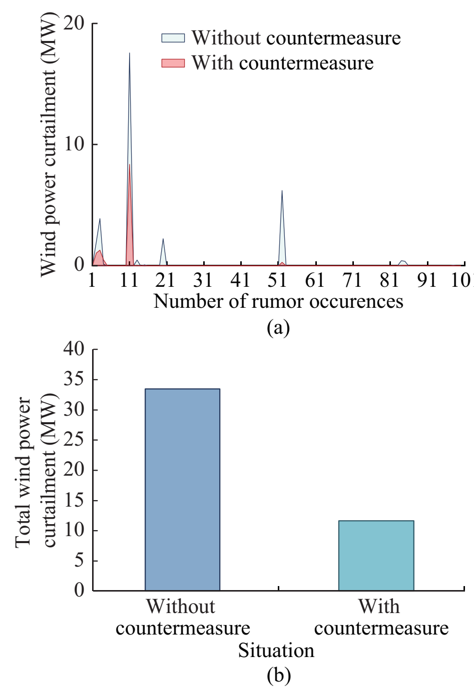

Fig. 16. Impacts of countermeasures on changes of wind power curtailments and total power wind power curtailments. (a) Wind power curtailments. (b) Total wind power curtailments.

V. Conclusion

In this study, we present an in-depth analysis of the possible impact of rumors related to electricity market, and develop a two-layer network model (EM-SIS) to characterize the couplings of rumor propagation and electricity market operation.

Numerical simulations demonstrate the serious implications of rumor propagation in the context of electricity market operation, particularly with a high penetration level of renewables. To respond the threat of rumors relevant to electricity market operation, we suggest the following measures.

1) Strengthen the training of market entities to improve their ability to identify rumors during information sharing.

2) Enrich the information resources at official platforms for market entities to better verify the truthfulness of potential rumors such as establishing a rumor detection and notification platform for the electricity market.

3) Develop emergency mechanisms for electricity market to improve the inherent capability of market operation against rumors. For example, redo market bidding and clearing when the market operation performance exhibits a significant deviation.

Finally, this study can inspire more interdisciplinary investigations on the interactions between information, society, electricity infrastructure, and electricity markets toward power system modernization.

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Xiangyu Ma received the B.S. degree in electrical engineering from China University of Mining and Technology, Xuzhou, China, in 2019. He is currently working toward the M.S. degree in electrical engineering with the Polytechnic Institute, Zhejiang University, Hangzhou, China. His research interests include electricity market and power system resilience.

Zhiyi Li received the Ph.D. degree from the Department of Electrical and Computer Engineering Department, Illinois Institute of Technology, Chicago, USA, in 2017. From August 2017 to May 2019, he was a Senior Research Associate with the Robert W. Galvin Center for Electricity Innovation, Illinois Institute of Technology. Since June 2019, he has been a Tenure-Track Assistant Professor with the College of Electrical Engineering, Zhejiang University, Hangzhou, China. His research interests include cyber-physical systems and power system optimization.

Huanhai Xin received the Ph.D. degree from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, in 2007. He was a Postdoctoral Researcher with the Electrical Engineering and Computer Science Department, University of Central Florida, Orlando, USA, from June 2009 to July 2010. He is currently a Professor with the Department of Electrical Engineering, Zhejiang University. His research interests include power system stability analysis and renewable energy integration.