Received 3 August 2022, accepted 21 August 2022, date of publication 26 August 2022, date of current version 31 August 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3201892

RESEARCH ARTICLE

Congestion Identification and Expansion Planning Methods of Transmission System Considering Wind Power and TCSC

FAN CHEN[1,2], JIANLIN LIU[1], MEILIAN ZHAO[1,2], AND HAITAO LIU[1,2]

[1]Jiangsu Collaborative Innovation Center for Smart Distribution Network, Nanjing Institute of Technology, Nanjing 211167, China
[2]State Key Laboratory of Smart Grid Protection and Control, Nanjing 211006, China

Corresponding author: Fan Chen (chenfan@njit.edu.cn)

This work was supported in part by the State Key Laboratory of Smart Grid Protection and Control of China under Grant SGTYHT/20-JS-221, in part by the Scientific Research Fund of Nanjing Institute of Technology of China under Grant CKJB202001, and in part by the Project of Graduate Teaching Case Library Construction of Nanjing Institute of Technology of China under Grant 2021ALK08.

ABSTRACT Transmission congestion identification and expansion planning methods for power systems with wind power are proposed in this paper. First, wind farm model is established based on Copula theory considering the uncertainty and correlation of wind speed and wind turbine's failure. Next, generation rescheduling model with wind farm and TCSC is established and a transmission congestion identification method based on reliability evaluation is proposed. Then, alternative schemes of expansion planning have been proposed according to the results of congestion identification, and the final scheme is determined by probabilistic economic analysis method. Finally, case studies have been carried out on modified RBTS test system. For the mRBTS system, when wind farms are integrated into system from bus 1 and 2, the best expansion solution is to build new transmission line; while when wind farms are integrated from bus 3 and 5, the best expansion solution is to install TCSC. Results of case studies verify the effectiveness of the proposed congestion identification and expansion planning methods of transmission system, and reveal that the location of wind power affects the decision making of transmission system expansion planning scheme.

INDEX TERMS Expansion planning, transmission congestion, TCSC, wind farm, reliability assessment.

I. INTRODUCTION

With the widely development of wind power generation over the world, the large-scale integration of wind power into power systems may cause transmission congestion [1]. The output of wind power has great uncertainty [2], which increases the complexity of expansion planning to alleviate transmission congestion. Meanwhile, thyristor controlled series compensation (TCSC) can enhance the transmission capacity by controlling the line power flow without changing the topology of power grid [3], and thus has been adopted in real power systems to alleviate transmission congestion. Therefore, it is meaningful to study congestion identification and expansion planning methods of transmission system considering wind power and TCSC.

Generally, transmission congestion occurs at some specific lines, while other lines have low load rate and still have large spare capacity at the same time. Therefore, it is necessary to identify the lines with transmission congestion, so as to take enhanced measures to alleviate or eliminate transmission congestion. In [4], from the perspective of load curtailment, weak positions of transmission congestion were identified by allocating load curtailments caused by transmission congestion to each faulty component. However, it only studied the causes of transmission congestion and proposed no measures to relieve transmission congestion. A congestion status identification method based on unsupervised machine learning techniques with locational marginal price (LMP) data is proposed in [5], but all of the basis vectors of LPM need to be detected. In [6], an analytical method for transmission congestion identification is proposed. However, this method can only answer whether transmission congestion occurs or not, and cannot quantify the severity of congestion. On the other hand,

The associate editor coordinating the review of this manuscript and approving it for publication was Zhouyang Ren.

the output of wind farm is usually represented by multistate model, which increases the complexity of transmission congestion identification for power systems with wind power. To the best of our knowledge, there is little articles studying transmission congestion identification method considering wind power integration. In this paper, we propose a transmission congestion identification method for power systems with wind power, which can directly reflect the severity of congestion and is simple and easy to implement.

To alleviate transmission congestion, some researchers studied on expansion planning methods for modern power systems. In [7], [8], and [9], TCSC and other devices were installed to enhance the transmission capacity. In [10], [11], and [12], probabilistic characteristics of modern power systems such as the uncertainty of wind power generation have been considered in the expansion planning process. In [10], the uncertainty of wind power was considered when the planning scheme is formed, which makes the system analysis process more complex and the solution of transmission system planning model more difficult. In order to address the difficulty of solving optimal model of transmission system planning caused by introducing probability factors, the multi-stage planning model was proposed in [11] and [12]. However, the process of introducing probability factors into system planning scheme is still complicated. Different from introducing probability factors in the formation stage of planning schemes, it was pointed out in [13] that introducing probability factors in the comprehensive economic comparison stage is simple and more practical, which inspires us to study the expansion planning method of modern power systems by considering the uncertainty of wind power in the comprehensive economic comparison stage of system planning. To sum up, there are few existing papers that carry out expansion planning for alleviating transmission congestion. Some papers only considered TCSC without considering wind power integration, while other papers only considered wind power integration without considering TCSC. As for the uncertainty of wind power, most existing papers addressed the uncertainty in the formation stage of power system expansion planning, and thus made the planning model complicated and hard to solve. In this context, there is need to study transmission expansion planning for power systems considering both wind power and TCSC, and try to reduce the complexity of the planning model by addressing the uncertainty of wind power in the comprehensive comparison stage.

In this paper, we study the transmission congestion identification method for power systems with wind power and the probabilistic transmission expansion planning method considering wind power and TCSC. The main contributions of our work are as follows:

(1) A transmission congestion identification method based on reliability evaluation of composite power systems is proposed.

(2) An expansion planning method of transmission system is proposed based on congestion identification results and probabilistic economic analysis theory.

(3) The impacts of wind power and TCSC on transmission congestion and expansion planning have been studied.

The sections of this paper are structured as follows. Sections II and III describe probabilistic model of wind farm and generation rescheduling model considering wind power and TCSC. Section IV presents the methods of transmission congestion identification and transmission expansion planning. Case studies have been illustrated in Section V. Finally, conclusions are made in Section VI.

II. UNCERTAINTY MODELING OF WIND POWER

The fluctuation and intermittency characteristics of wind speed and the random faults of wind turbines make the output of wind farm strong uncertain. And on the other hand, the random faults of wind turbines in wind farm show certain correlation with wind speed.

In this paper, Weibull distribution is adopted to simulate the uncertainty of wind speed in wind farms, and the probability density function of wind speed is calculated by:

$$F(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} exp[-(\frac{v}{c})^{k}] \tag{1}$$

where, v is the wind speed of wind farm, c and k are the scale parameter and shape parameter of Weibull distribution respectively.

In order to characterize the uncertainty of wind turbine random fault, a two-state (normal operation state and fault outage state) Markov model is adopted to deal with the uncertainty of wind turbine failure, and the forced outage rate of wind turbine is calculated by:

$$r = \frac{\lambda}{\lambda + \mu} = \frac{t_{\mathrm{MTTR}}}{t_{\mathrm{MTTF}} + t_{\mathrm{MTTR}}} \tag{2}$$

where, λ and μ respectively represent the failure rate and repair rate of the wind turbine; t_{MTTF} and t_{MTTR} respectively represent the mean time to failure and mean time to repair of the wind turbine.

By establishing Copula function to simulate wind speed and the number of failed wind turbines [14], the correlation between wind farm wind speeds can be processed. After generating the hourly wind speed sequence of each wind farm and the fault number of wind turbines based on Copula function, combined with the output power characteristics of wind turbine, the hourly output power sequence of each wind farm can be obtained. The hourly output power sequence of the i^{th} wind farm considering wind turbine failure can be calculated by [15]:

$$P_i(t) = [m_i - n_{fi}(t)] \times PN_i(t) \tag{3}$$

where, $PN_i(t)$ is the output of a single wind turbine unit during normal operation, m_i is the number of wind turbines in the i^{th} wind farm, and $n_{fi}(t)$ is the number of wind turbines in fault in the i^{th} wind farm at time t.

The probability of occurrence of each equivalent state can be calculated by linear division of the duration corresponding to the hourly output power of the sum of wind farm outputs. The detailed steps can be seen in [15].

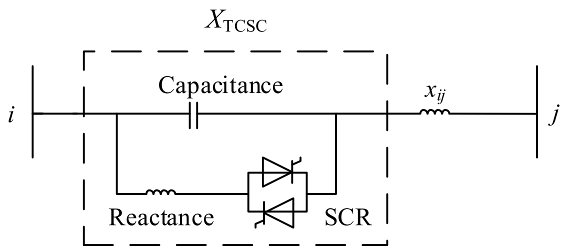

FIGURE 1. Equivalent model of transmission line with TCSC.

III. GENERATION RESCHEDULING MODEL WITH WIND POWER AND TCSC

A. MATHEMATICAL MODEL OF TRANSMISSION LINE WITH TCSC

TCSC can control power flow of transmission lines by adjusting line impedance parameters and thus it is helpful for alleviating transmission congestion. The topology of the TCSC main circuit is very simple, with capacitors connected in series to the transmission line and thyristor controlled reactors connected in parallel. It does not need interface equipment such as high voltage transformer, and it is easy to reconstruct the existing conventional series complement station, so it is very economical. It is worth pointing out that TCSC has both capacitive and inductive impedance characteristics [16], and can switch quickly between the two. This fast and flexible ''impedance type'' control can be used to control active power of systems. The equivalent model of the transmission line equipped with TCSC [17] is shown in Fig. 1.

The active power of line ij without TCSC can be calculated by:

$$P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \tag{4}$$

where, P_{ij} is the active power flow of line ij, θ_i and θ_j is the voltage angle of bus i and j respectively, x_{ij} is transmission line reactance without TCSC.

When TCSC was installed, the active power of line ij is calculated by:

$$P_{ij} = \frac{\theta_i - \theta_j}{x_{ij} + X_{TCSC}} \tag{5}$$

where, X_{TCSC} is the equivalent reactance of TCSC.

Then, the equivalent reactance of line ij is transformed into [18]:

$$x_{ij}^{new} = x_{ij} + X_{TCSC} \tag{6}$$

where, x_{ij}^{new} is the overall reactance of line ij when TCSC was installed.

B. LOAD CURTAILMENT MODEL CONSIDERING WIND POWER AND TCSC

When transmission capacity is insufficient, power generation rescheduling is needed to reduce load curtailments as far as possible. The load curtailment model of power systems including wind farm and TCSC is as follows [19]:

$$\min \sum_{i \in ND} C_i \tag{7}$$

Constraints:

$$\sum_{i \in NG} PG_i + \sum_{i \in ND} C_i + \sum_{i \in NWF} G_{WF,i} = \sum_{i \in ND} PD_i \tag{8}$$

$$PG_i^{min} \le PG_i \le PG_i^{max}, \quad (i \in NG) \tag{9}$$

$$0 \le C_i \le PD_i, \quad (i \in ND) \tag{10}$$

$$\boldsymbol{TS} = \boldsymbol{AS}(\boldsymbol{PG} - \boldsymbol{PD} + \boldsymbol{C}) \tag{11}$$

$$-T_k^{max} \le TS_k \le T_k^{max}, \quad (k \in L) \tag{12}$$

$$X_{i,min} \le X_{TCSC,i} \le X_{i,max}, \quad (i \in N_{TCSC}) \tag{13}$$

where, C_i, PG_i, PD_i and $G_{WF,i}$ represent load curtailment, generating capacity of traditional unit, load power and injected power of wind farm respectively at bus i; NG, ND and NWF respectively represent the number of generation buses, load buses and wind farms connected to the bus; PG_i^{min} and PG_i^{max} are the limits of PG_i; $\boldsymbol{PG}$, $\boldsymbol{PD}$ and $\boldsymbol{C}$ are vectors composed of PG_i, PD_i and C_i respectively; TS_k represents the active power of line k in the expected system state, L is the number of lines, $\boldsymbol{TS}$ is active power vector of transmission line corresponding to TS_k, T_k^{max} is the limit of TS_k, $X_{TCSC,i}$ represents the series compensation reactance of the i^{th} TCSC, $X_{i,max}$ and $X_{i,min}$ represent the upper and lower limits of compensation reactance of the i^{th} TCSC, N_{TCSC} is the number of TCSC installed in the system; $\boldsymbol{AS}$ is the relationship matrix between active power flow of transmission line and bus injected power under accident state.

It is worth pointing out that the load curtailment model for power systems without TCSC can be represented by Eq. (7)-(12). That is to say, the constraint of Eq. (13) doesn't need to be contained if no TCSC is integrated into power systems.

IV. CONGESTION IDENTIFICATION AND EXPANSION PLANNING OF TRANSMISSION SYSTEM BASED ON RELIABILITY ASSESSMENT

A. TRANSMISSION CONGESTION IDENTIFICATION METHOD BASED ON RELIABILITY ASSESSMENT

Based on generation rescheduling model considering wind farm and TCSC, this paper proposes a transmission congestion identification method based on reliability assessment, which can be used to identify the lines with serious transmission congestion, and provide a basis for preliminary formation of the planning scheme.

It is considered that system load curtailments may be caused by insufficient generation capacity or insufficient transmission capacity. Therefore, in order to accurately identify the load reduction caused by transmission congestion, we need to exclude the load reduction caused by insufficient generation capacity first. Based on this idea, we propose a transmission congestion identification method originated from composite power system reliability evaluation method. The main characteristic of the proposed method is as follows:

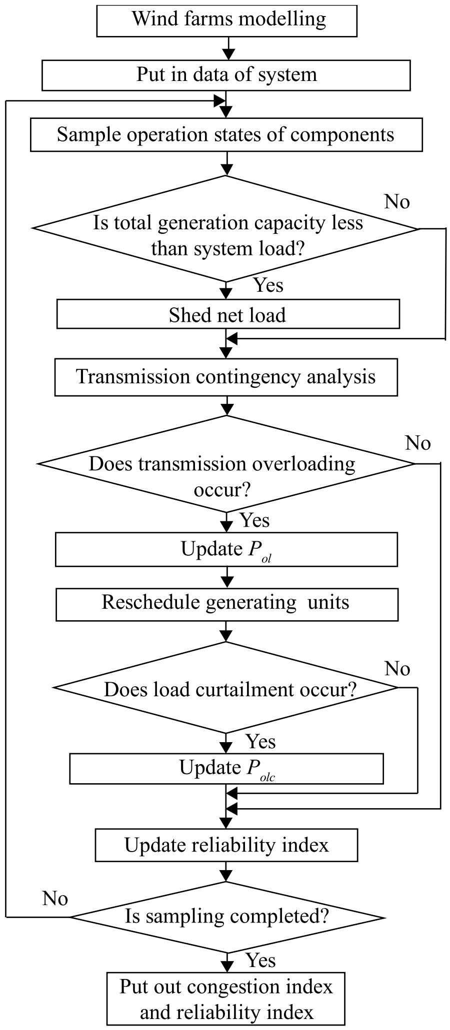

FIGURE 2. Flow chart for transmission congestion identification and reliability evaluation.

for the specific system states characterized by that the total capacity of generators in normal state is less than system load, extra shedding load step is implemented first before implementing consequent steps such as contingency analysis and rescheduling generating units. In the extra shedding load step, the net load between the total capacity of generators in normal state and system load is shed first and considered to be shed owing to generation power deficiency. Then, the following steps are similar with steps in conventional reliability evaluation process, and the load curtailment obtained in the following steps will be owned to transmission congestion. The flowchart for the transmission congestion identification and reliability evaluation of power systems is shown in Fig. 2.

The specific steps corresponding to Fig.2 are as follows:

Step 1: Create wind farm model considering uncertainty and correlations. The detailed steps to build multistate models of wind farms considering multiple uncertain factors can be reviewed in [15].

Step 2: Put in system data, including topological parameters, reliability parameters, electrical characteristic parameters, and access locations of wind farms.

Step 3: Sample operation states of components including generators and transmission lines using Monte Carlo method.

Step 4: Compare the total capacity of the generators in normal state with the system load. If the total capacity of generators in normal state is less than the system load, continue with the next step; otherwise, go to Step 6.

Step 5: Shed net load. The net load is defined as the difference between total capacity of generators in normal state and system load. The net load is shed using average shedding policy. According to this average policy, all loads at the buses are curtailed with a same proportion when load curtailments are implemented.

Step 6: Carry out transmission contingency analysis.

The purpose of transmission contingency analysis is to calculate line flows following one or more component failures and identify if there is any overloading. DC power-flow-based contingency analysis provides fast and sufficiently accurate real power flows following line outages [19].

The bus impedance matrices after multiple line outages can be calculated directly from the bus impedance matrix before the outages:

$$\boldsymbol{ZS} = \boldsymbol{Z0} + \boldsymbol{Z0MQM^T Z0} \tag{14}$$
$$\boldsymbol{Q} = [\boldsymbol{W} - \boldsymbol{M^T Z0M}] \tag{15}$$

where, $\boldsymbol{Z0}$ and $\boldsymbol{ZS}$ are the bus impedance matrices before and after the line outages. $\boldsymbol{W}$ is the diagonal matrix whose each diagonal element is the reactance of the outage line. $\boldsymbol{M}$ is the submatrix composed of the columns corresponding to the outage lines of the bus-line incidence matrix. $\boldsymbol{M^T}$ is the transpose matrix of $\boldsymbol{M}$.

The line flows after line outages can be calculated by:

$$\boldsymbol{TS} = \boldsymbol{AS}(\boldsymbol{PG} - \boldsymbol{PD}) \tag{16}$$

where, $\boldsymbol{TS}$ is the real power flow vector in the outage state. $\boldsymbol{PG}$ and $\boldsymbol{PD}$ are the generation output and load power vectors, respectively. $\boldsymbol{AS}$ is the relation matrix between the real power flows and power injections in the outage state.

The m^{th} row of $\boldsymbol{AS}$ can be calculated as follows:

$$\boldsymbol{AS}_m = \frac{\boldsymbol{ZS}_r - \boldsymbol{ZS}_q}{x_m} \tag{17}$$

where, x_m is the reactance of the m^{th} line, the subscripts r and q denote the two bus numbers of the m^{th} line, $\boldsymbol{ZS}_r$ and $\boldsymbol{ZS}_q$ are the r^{th} and q^{th} rows of $\boldsymbol{ZS}$, respectively.

Transmission congestion occurs when the line flow is greater than the rated capacity of the line. Transmission overloading can be represented as follows:

$$|TS_k| > T_k^{max}, \quad (k \in L) \tag{18}$$

where, T_k^{max} is the limit of TS_k.

Step 7: If there is any transmission overloading, continue with the next step; otherwise, go to Step 12.

Step 8: Update P_{ol}.

$$P_{ol}(i) = \frac{M_{ol}(i)}{NS} \tag{19}$$

where, $P_{ol}(i)$ is probability of events that transmission congestion occur at line i; $M_{ol}(i)$ is the number of occurrences of events that transmission congestion occurs at line i in NS samples.

Step 9: Reschedule generating units based on optimal load curtailment model representing by Eq. (7)-(12). It is pointed out that Eq. (7)-(13) would be used for rescheduling generating units of power systems with TCSC.

Step 10: If load curtailment occurs, continue with the next step; otherwise, go to Step 12.

Step 11: Update P_{olc}.

$$P_{olc}(i) = \frac{M_{olc}(i)}{NS} \tag{20}$$

where, $P_{olc}(i)$ is the probability of event that transmission congestion occurs at line i companying with system load curtailment; $M_{olc}(i)$ is the number of occurrences of event that transmission congestion occurs at line i companying with system load curtailment in NS samples.

Step 12: Update reliability index of power systems.

Probability of Load Curtailments (PLC) and Expected Energy Not Supplied (EENS, MWh/year) are two most commonly used index to characterize reliability of power systems, and they can be calculated by [19]:

$$PLC = \frac{ns}{NS} \tag{21}$$

$$EENS = \sum_{i=1}^{NS} \left(\frac{CS_i}{NS} \times 8760\right) \tag{22}$$

where, NS is the sampling number, ns is the number of load shedding states, and CS_i is system load curtailment of system state i. It is pointed out that the reliability index of power systems will be used for determine final planning scheme through probabilistic economic analysis, which will be introduced in Section B.

Step 13: If the Monte Carlo sampling is completed, continue with the next step; otherwise go to Step 3.

Step 14: Put out congestion index of transmission lines and reliability index of power systems.

B. EXPANSION PLANNING OF TRANSMISSION SYSTEM BASED ON CONGESTION IDENTIFICATION RESULTS

Building new transmission line is an important measure to alleviate transmission congestion. However, when building new transmission line is limited by some reasons such as transmission corridor construction and environmental protection, TCSC equipment can be installed to alleviate transmission congestion. Based on the results of transmission congestion identification, this paper proposes a transmission expansion planning method by using probabilistic economic analysis theory. In probabilistic economic analysis theory, kinds of costs including investment cost, operation cost and unreliability cost are summed for final choose of alternative schemes. The specific steps are as follows:

Step 1: Determine the congestion lines according to the proposed transmission congestion identification method in A of Section IV.

Step 2: Develop preliminary alternative schemes for expansion planning.

Scheme A1: Install TCSC in the lines with serious congestion according to the results of transmission congestion identification.

Scheme A2: Build a new line between two buses with serious congestion according to the result of transmission congestion identification.

Step 3: Calculate power system reliability index of alternative schemes.

Step 4: Calculate unreliability costs of alternative schemes.

Unreliability cost is the key factor for comprehensive economic analysis, and its random nature makes economic analysis with probability characteristic. The unreliability cost is usually represented by the Expected Interruption Cost (EIC, k$/year) of the system, which can be calculated by [20]:

$$EIC = EENS \times UIC \tag{23}$$

where UIC ($/kWh) is the unit interrupted cost.

Step 5: Calculate equivalent annual investment costs of alternative schemes.

The investment cost is one-time payment, while the unreliability cost is annual expenses. Thus, there is need to convert investment cost into equivalent annual cost. Based on the equivalent annual cost method, the present cost P can be converted into equivalent annual cost A by:

$$A = P \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{24}$$

where i is the discount rate and n is the length of cash flows (the number of years considered).

Step 6: Calculate total costs of alternative schemes by summing unreliability cost, equivalent annual investment cost and annual operation cost.

Step 7: Compare total costs of alternative schemes and determine the final expansion scheme.

V. CASE STUDIES

A. INTRODUCTION OF TEST SYSTEM

In order to analyze the influence of wind power integration on transmission system expansion planning, the reliability test system RBTS system [21] was modified in this paper. The mRBTS system was obtained from RBTS system by modification as follows: 1) Add a new line (L10) between bus 5 and 6, and the parameters are the same as the original line; 2) Increase the load of all buses in the system by 1.3 times; 3) Add a new 20MW generator set at bus 2 with the same parameters as the original 20MW generator set at bus 2; 4) Add a new 20MW generator set at bus 1 with the same parameters as the original 20MW generator set at bus 1. The single line diagram of mRBTS system is shown in Fig. 3. It is pointed out that dotted line L11 in Fig.3 is not transmission

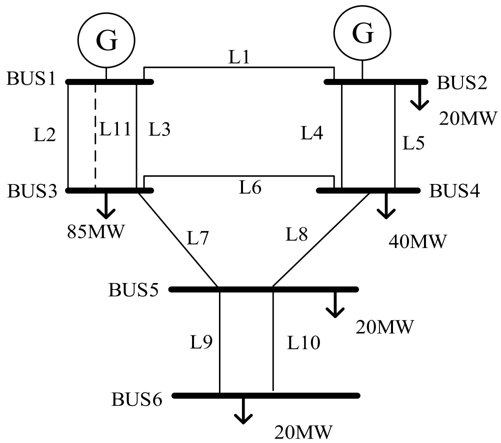

FIGURE 3. Single line diagram of mRBTS system.

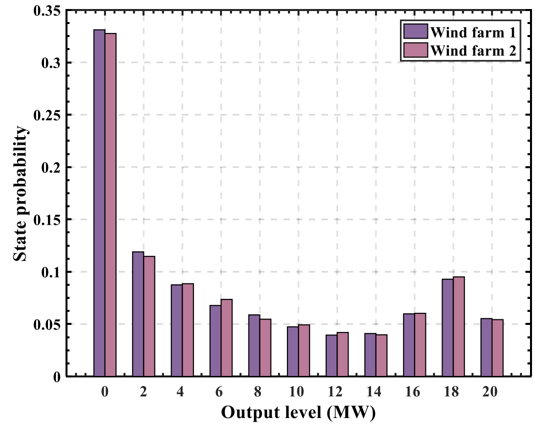

FIGURE 4. State probability models of wind farms.

line of mRBTS system but the proposed new line to be built in the following expansion planning scheme.

Two wind farms were integrated into mRBTS to form as mmRBTS system. It is assumed that the Weibull parameters of wind speeds of the two wind farms are the same: the scale parameter are both 7.5, the shape parameter are both 2, and the correlation coefficient of wind speed between the two wind farms is 0.5. The wind turbines of the two wind farms are of the same type. The cut-in wind speed, cut-out wind speed and rated wind speed of the wind turbines are 4m/s, 22m/s and 10m/s respectively. The rated power of the wind turbines is 2 MW, and the forced outage rate of the wind turbines is 0.05. This paper studies the impact of wind farms on expansion planning by connecting them to the system from different locations. For convenience, mmRBTS system with wind farms being connected at bus 1 and 2 respectively is called mmRBTS_WFa system, and mmRBTS system with wind farm being connected at bus 3 and 5 is called mmRBTS_WFb system.

According to the wind farm modeling method proposed in [15], the uncertainty of wind power considering wind speed correlation, wind turbine random failure and other factors can be represented by multistate models. As shown in Fig. 4, multistep output power with its corresponding state probability of two wind farms have been established.

B. CONGESTION IDENTIFICATION AND TRANSMISSION EXPANSION PLANNING OF MMRBTS_WFa SYSTEM

Line congestion index of mmRBTS_WFa and its enhanced systems are shown in Table 1. For demonstration purposes, we show M_{ol} and M_{olc} under 100,000 samples instead of P_{ol} and P_{olc} in the following tables, where M_{ol} represents the number of occurrences of events that transmission congestion occurs at specified line in 100,000 samples, and M_{olc} represents the number of occurrences of event that transmission congestion occurs at specified line companying with system load curtailment in 100,000 samples.

As shown in Table 1, L2 and L3 are seriously congested lines of mmRBTS_WFa system. Therefore, scheme A1 of installing TCSC devices on lines L2 and L3 (called mmRBTS_WFa _A1 system) and scheme A2 of building new transmission line L11 between bus 2 and 3 (called mmRBTS_WFa_A2 system) are proposed as alternative schemes. The series compensation degree of TCSC adopted is [−0.5, 0.5], the reliability parameters of the new line are the same as the original line between buses, and the capacity is 65% of the original line capacity. As can be observed in Table 1, M_{ol} and M_{olc} index have slight decrease when the scheme of installing TCSC is adopted; conversely, M_{ol} and M_{olc} are greatly reduced when the scheme of building new transmission line is adopted. This observation means that transmission congestion still exists in L2 and L3 of mmRBTS_WFa _A1 system, while transmission congestion disappears in L2 and L3 of mmRBTS_WFa_A2 system. The observation reveals that the scheme of installing TCSC cannot eliminate most of congestion contingencies while the scheme of building new line can greatly reduce many congestion contingencies.

TABLE 1. Line congestion index for mmRBTS_WFa system and its enhanced system (under 100,000 samples).

Line	mmRBTS_WFa system		mmRBTS_WFa _A1 system		mmRBTS_WFa _A2 system	
	M_{ol}	M_{olc}	M_{ol}	M_{olc}	M_{ol}	M_{olc}
L1	0	0	0	0	0	0
L2	178	177	176	175	0	0
L3	165	164	145	145	0	0
L4	8	8	8	6	3	3
L5	4	4	5	4	1	1
L6	0	0	0	0	0	0
L7	0	0	0	0	0	0
L8	0	0	0	0	0	0
L9	0	0	0	0	0	0
L10	0	0	0	0	0	0
L11	/	/	/	/	0	0

Then, reliability index of mmRBTS_WFa and its enhanced systems are shown in Table 2. As shown in Table 2, when the scheme of installing TCSC is adopted, EENS index is greatly reduced while PLC index has slight decrease; when

TABLE 2. Reliability index for mmRBTS_WFa System and its enhanced system.

Reliability index	Case system		
	mmRBTS_WFa	mmRBTS_ WFa _A1	mmRBTS_ WFa _A2
PLC	0.0081	0.0079	0.0045
EENS(MWh/year)	1023.83	419.34	324.86

the scheme of building new transmission line is adopted, EENS and PLC are both greatly reduced. The observation reveals that the scheme of installing TCSC contributes to reduce the amount of load curtailment but fails to reduce the probability of shedding load.

To illustrate transmission congestion when some components fail, we especially investigated the power flow of transmission lines in some scenarios that only one or two transmission lines fail. In these scenarios when only transmission lines fail, the generation capacity is sufficient and thus system load curtailment is irrelated with wind power generation. For simplicity, we set the wind farm output to 0 MW during the process of calculation. The results of system load curtailment and power flows of normal lines are shown in Table 3. In Table 3, the first column shows the line label; the second column shows the rated capacity of lines (MW); the third column shows power flow of lines (MW) when no components fail; columns four through six show power flows of lines (MW) when specified lines fail with the assumption that the capacities of remaining lines are not limited; the last row shows system load curtailments in different system states.

As shown in Table 3, transmission congestion and load curtailment occur when line L2 fails, while transmission congestion and load curtailment do not occur when line L4 fails. And specifically, the amount of load curtailment when line L2 fails is greater than the amount when both line L1 and L5 fail. At the same time, the probability of line L2 fails is larger than the probability of line L1 and L5 fails simultaneously. Thus, we can conclude that the congestion consequence of event that L2 fails is larger than that of event that line L1 and L5 both fail, which is consistent with the congestion identification results in this paper.

The equivalent annual cost method is used to make a comprehensive economic comparison among three schemes, including A0 (the scenario without expansion measures), A1 and A2 planning schemes. Relevant data needed in the process of economic comparison are as follows: unit interruption cost of mmRBTS system is 4.59$/kWh [22]; The unit cost of TCSC equipment is $40/kvar [23], and the service life of TCSC is 10 years; The length of the new line between bus 1 and bus 3 is 75km, the unit cost of 230kV line is $20,000/km, and the service life of the line is 30 years [21], [24]. The discount rate is 10% and the annual operation cost is 5% of the equivalent investment cost. For simplicity, the sum

TABLE 3. Power flow of normal lines and load curtailment in case of partial line contingencies for mmRBTS_WFa system.

Line	Capacity	Fault -free	Faulty line		
			L2	L4	L1 and L5
L1	71.00	33.22	22.30	54.41	/
L2	85.00	63.11	/	73.70	46.50
L3	85.00	63.11	**115.30**	73.70	46.50
L4	71.00	44.14	49.60	/	**121.50**
L5	71.00	44.14	49.60	67.09	/
L6	71.00	6.85	14.13	7.27	29.00
L7	71.00	22.57	18.93	29.64	11.50
L8	71.00	29.42	33.07	22.36	40.50
L9	71.00	13.00	13.00	13.00	13.00
L10	71.00	13.00	13.00	13.00	13.00
load curtailment		0.00	**24.08**	0.00	**13.50**

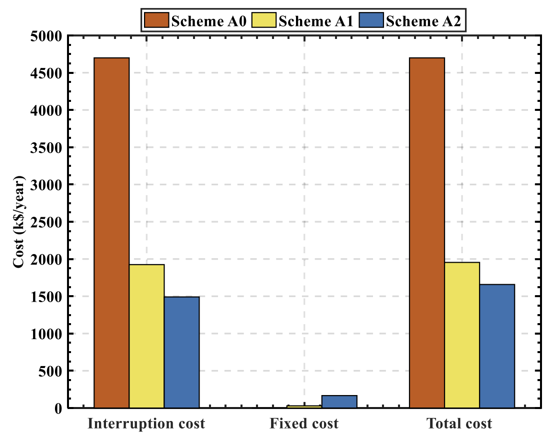

FIGURE 5. Comprehensive economic comparison of alternative schemes for mmRBTS_WFa system.

of equivalent annual investment cost and annual operation cost is called as fixed cost, and then the comprehensive economic comparison is shown in Fig. 5. The comparison of specific values of costs can be seen in Table 6 in the Appendix.

As can be seen in Fig. 5, when wind farm is connected into system from bus 1 and 2, both of enhancement schemes have good economic benefits, and scheme A2 of building new line is more economical, though the equivalent annual cost of building new transmission line is greater than that of TCSC installation. The reason lies in that when the wind farm is connected from bus 1 and bus 2, the generation power is still concentrated in the north and needs to be transmitted into the load center in the south, which thus worsen the transmission congestion and limit TCSC's effect for alleviating transmission congestion. In this situation, the two schemes have a large gap in their ability to alleviate transmission congestion, which makes the interruption cost of scheme A1much larger

TABLE 4. Line congestion index for mmRBTS_WFb system and its enhanced system (under 100,000 samples).

Line	mmRBTS_WFb system		mmRBTS_WFb_ A1 system		mmRBTS_WFb_ A2 system	
	M_{ol}	M_{olc}	M_{ol}	M_{olc}	M_{ol}	M_{olc}
L1	0	0	0	0	0	0
L2	174	145	160	120	1	0
L3	159	132	157	119	0	0
L4	8	5	3	1	1	1
L5	4	3	1	1	1	0
L6	0	0	0	0	0	0
L7	0	0	0	0	0	0
L8	0	0	0	0	0	0
L9	0	0	0	0	0	0
L10	0	0	0	0	0	0
L11	/	/	/	/	1	1

TABLE 5. Reliability index for mmRBTS_WFb system and its enhanced system.

Reliability index	Case systems		
	mmRBTS_WFb	mmRBTS_ WFb_A1	mmRBTS_ WFb_A2
PLC	0.0075	0.0070	0.0040
EENS(MWh/year)	789.20	307.40	294.51

than that of scheme A2, and finally the total cost of the scheme A1 larger than that of scheme A2.

C. CONGESTION IDENTIFICATION AND TRANSMISSION EXTENSION PLANNING OF MMRBTS_WFb SYSTEM

Similarly, transmission congestion and reliability index of mmRBTS_WFb system are evaluated. Line congestion index and reliability index of mmRBTS_WFb and its enhanced systems are shown in Table 4 and 5 respectively.

Table 4 shows that there is transmission congestion in line L2 and L3 of mmRBTS_WFb system, and observations from Table 1 can also be concluded in Table 4. In addition, M_{ol} and M_{olc} of mmRBTS_WFb system is less than those in mmRBTS_WFa system, which indicates that the degree of transmission congestion is alleviated when wind farms are connected into system from bus 3 and 5.

Similarly, observations from Table 2 can also be concluded in Table 5. It is noted that index in Table 5 are smaller than those corresponding index in Table 2, which reveals the impact of integrated locations of wind power on transmission congestion again.

Probabilistic economic cost comparison of alternative expansion schemes of mmRBTS_WFb system is shown in Fig. 6. The comparison of specific values of costs can be seen in Table 7 in the Appendix. As can be seen in Fig. 6 (when the wind farms are connected into system at bus 3 and 5), scheme A1 is more economical than scheme A2, while the previous Fig. 5 (when the wind farms are connected into system at bus 1 and 2) shows that scheme A2 is more economical. Thus, it can be concluded that the economical comparison results among expansion schemes may be different if wind

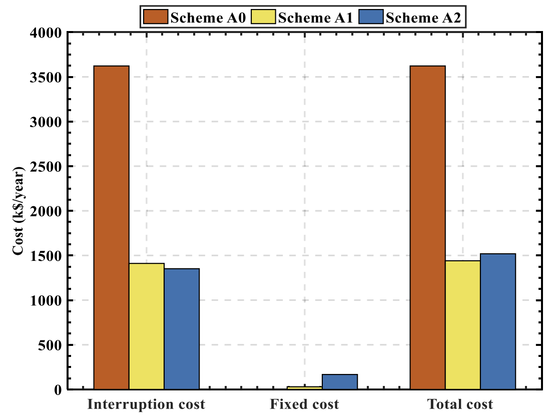

FIGURE 6. Comprehensive economic comparison of alternative schemes for mmRBTS_WFb system.

TABLE 6. Comprehensive economic comparison of alternative schemes for mmRBTS_WFa system.

Scheme	Interruption cost (k$/year)	Fixed cost (k$/year)	Total cost (k$/year)
A0	4699.38	0	4699.38
A1	1924.77	29.62	1954.39
A2	1491.11	167.11	1658.21

TABLE 7. Comprehensive economic comparison of alternative schemes for mmRBTS_WFb system.

Scheme	Interruption cost (k$/year)	Fixed cost (k$/year)	Total cost (k$/year)
A0	3622.43	0	3622.43
A1	1410.97	29.62	1440.59
A2	1351.80	167.11	1518.91

farms are connected into system at different locations. For the test system in this paper, when wind farms are connected into system at bus 3 and 5, the wind power can be directly transmitted to the load. Therefore, it will not worsen transmission congestion and TCSC can better alleviate transmission congestion. In this case, there is little gap between the two alternative schemes in alleviating transmission congestion. Therefore, there is little gap between the interruption costs. When the fixed cost of building new transmission line is much larger than that of installing TCSC, the total cost of scheme A2 is larger than that of scheme A1.

VI. CONCLUSION

A transmission congestion identification method and a transmission expansion planning method for power systems considering wind power are proposed in this paper. Taking the modified RBTS test system as an example, we can conclude as follows:

(1) The proposed transmission congestion identification method can effectively determine the serious congestion

lines, and the proposed expansion planning method can provide reliable planning scheme economically.

(2) The access locations of wind power have impact on transmission congestion index and the results of comprehensive economic comparison, and it is necessary to carry out quantitative reliability assessment and probabilistic economic analysis before forming the final expansion planning scheme.

APPENDIX

See Tables 6 and 7.

REFERENCES

[1] Y. Huang, Q. Xu, and G. Lin, "Congestion risk-averse stochastic unit commitment with transmission reserves in wind-thermal power systems," *Appl. Sci.*, vol. 8, no. 10, Sep. 2018, Art. no. 1726.

[2] C. A. Moraes, L. W. de Oliveira, E. J. de Oliveira, D. F. Botelho, A. N. de Paula, and M. F. Pinto, "A probabilistic approach to assess the impact of wind power generation in transmission network expansion planning," *Electr. Eng.*, vol. 104, no. 2, pp. 1029–1040, Apr. 2022.

[3] T. T. Nguyen and F. Mohammadi, "Optimal placement of TCSC for congestion management and power loss reduction using multi-objective genetic algorithm," *Sustainability*, vol. 12, no. 7, p. 2813, Apr. 2020.

[4] M. Gan, K. Xie, and C. Li, "Transmission congestion tracing technique and its application to recognize weak parts of bulk power systems," *J. Mod. Power Syst. Clean Energy*, vol. 5, no. 5, pp. 725–734, Sep. 2017.

[5] K. Zheng, Q. Chen, Y. Wang, C. Kang, and L. Xie, "Unsupervised congestion status identification using LMP data," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 726–736, Jan. 2021.

[6] Y. Hu, P. Xun, W. Kang, P. Zhu, Y. Xiong, and W. Shi, "Power system zone partitioning based on transmission congestion identification using an improved spectral clustering algorithm," *Electronics*, vol. 10, no. 17, p. 2126, Sep. 2021.

[7] O. Ziaee and F. F. Choobineh, "Optimal location-allocation of TCSC devices on a transmission network," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 94–102, Jan. 2017.

[8] A. Sharma and S. K. Jain, "Gravitational search assisted algorithm for TCSC placement for congestion control in deregulated power system," *Electr. Power Syst. Res.*, vol. 174, Sep. 2019, Art. no. 105874.

[9] A. A. Sadiq, M. Buhari, S. S. Adamu, and H. Musa, "Coordination of multi-type FACTS for available transfer capability enhancement using PI–PSO," *IET Gener., Transmiss. Distrib.*, vol. 14, no. 21, pp. 4866–4877, Nov. 2020.

[10] G. Kim and J. Hur, "Probabilistic modeling of wind energy potential for power grid expansion planning," *Energy*, vol. 230, Sep. 2021, Art. no. 120831.

[11] M. Jadidoleslam, A. Ebrahimi, and M. A. Latify, "Probabilistic transmission expansion planning to maximize the integration of wind power," *Renew. Energy*, vol. 114, pp. 866–878, Dec. 2017.

[12] Q. Wang, X. Luo, H. Ma, and N. Gong, "Multi-stage stochastic wind-thermal generation expansion planning with probabilistic reliability criteria," *IET Gener., Transmiss. Distrib.*, vol. 16, no. 3, pp. 517–534, Feb. 2022.

[13] W. Y. Li, *Probabilistic Transmission System Planning*. Hoboken, NJ, USA: Wiley, 2011.

[14] F. Chen, F. Li, W. Feng, Z. Wei, H. Cui, and H. Liu, "Reliability assessment method of composite power system with wind farms and its application in capacity credit evaluation of wind farms," *Electr. Power Syst. Res.*, vol. 166, pp. 73–82, Jan. 2019.

[15] F. Chen, F. Li, Z. Wei, G. Sun, and J. Li, "Reliability models of wind farms considering wind speed correlation and WTG outage," *Electr. Power Syst. Res.*, vol. 119, pp. 385–392, Feb. 2015.

[16] S. Kamel, M. Abokrisha, A. Selim, and F. Jurado, "Power flow control of power systems based on a simple TCSC model," *Ain Shams Eng. J.*, vol. 12, no. 3, pp. 2781–2788, Sep. 2021.

[17] R. Agrawal, S. K. Bharadwaj, and D. P. Kothari, "Population based evolutionary optimization techniques for optimal allocation and sizing of thyristor controlled series capacitor," *J. Electr. Syst. Inf. Technol.*, vol. 5, no. 3, pp. 484–501, Dec. 2018.

[18] O. A. Mousavi, M. J. Sanjari, G. B. Gharehpetian, and R. A. Naghizadeh, "A simple and unified method to model HVDC links and FACTS devices in DC load flow," *Simulation*, vol. 85, no. 2, pp. 101–109, Feb. 2009.

[19] W. Y. Li, *Risk Assessment of Power Systems: Models, Methods, and Applications*. Hoboken, NJ, USA: Wiley, 2014.

[20] A. A. Chowdhury and D. O. Koval, "Application of customer interruption costs in transmission network reliability planning," *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, pp. 1590–1596, Nov./Dec. 2001.

[21] R. Billinton, S. Kumar, N. Chowdhury, K. Chu, K. Debnath, L. Goel, E. Khan, P. Kos, G. Nourbakhsh, and J. Oteng-Adjei, "A reliability test system for educational purposes-basic data," *IEEE Trans. Power Syst.*, vol. 4, no. 3, pp. 1238–1244, Aug. 1989.

[22] J. Oteng-Adjei and R. Billinton, "Evaluation of interrupted energy assessment rates in composite systems," *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1317–1323, Nov. 1990.

[23] J. Coevering, J. Stovall, R. Hauth, P. Tatto, B. Railing, and B. Johnson, "The next generation of HVDC-needed R&D, equipment costs, and cost comparisons," in *Proc. EPRI Conf. Future Power Del.*, Washington, DC, USA, 1996, pp. 9–11.

[24] R. Fang and D. J. Hill, "A new strategy for transmission expansion in competitive electricity markets," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 374–380, Feb. 2003.

FAN CHEN received the B.S. and M.S. degrees from Wuhan University, Wuhan, China, in 2004 and 2006, respectively, and the Ph.D. degree from Hohai University, Nanjing, China, in 2016. She is currently a Professor with the Nanjing Institute of Technology. Her research interests include power system planning and reliability, renewable energy integration in power systems, and power system optimization.

JIANLIN LIU received the B.S. degree from the Nanjing Institute of Technology, China, in 2020, where he is currently pursuing the M.S. degree. His research interests include power system planning and reliability assessment.

MEILIAN ZHAO received the B.S. degree from the Zhengzhou University of Technology, Zhengzhou, China, in 1999, and the M.S. degree from Guangxi University, Guangxi, China, in 2002. She is currently an Associate Professor with the Nanjing Institute of Technology. Her research interests include renewable energy integration in power systems and power system optimization.

HAITAO LIU received the Ph.D. degree from Southeast University, Nanjing, China, in 2009. She is currently a Professor with the Nanjing Institute of Technology. Her research interests include power system stability, energy storage, and power quality analysis.