Journal of Electrical Engineering & Technology (2021) 16:2367–2378
https://doi.org/10.1007/s42835-021-00775-9

ORIGINAL ARTICLE

A Study on Reliability and Capacity Credit Evaluation of China Power System Considering WTG with Multi Energy Storage Systems

Jingfeng Zhao[1] · Ungjin Oh[1] · Yeonchan Lee[1] · Joochang Park[1] · Jaeseok Choi[1]

Received: 10 February 2021 / Revised: 4 April 2021 / Accepted: 30 April 2021 / Published online: 1 July 2021

Abstract
Due to the uncertainty energy resources, the distributed renewable energy supply usually leads to the highly unstable reliability of power system. For instance, power system reliability can be affected by the high penetration of large-scale wind turbine generators (WTG). Therefore, energy storage system (ESS) is usually installed with the distributed renewable energy generation to improve the power system reliability by smoothing out the fluctuations and improve the supply and demand balance. This paper aims to analyze the power system reliability by developing the multi-ESSs coordinated with WTGs model, which is each ESS linked with each WTG. The main indices for reliability evaluation are loss of load expectation, expected energy not served and energy index of reliability. Monte Carlo simulation method is used in this study. Furthermore, this paper demonstrates various sensitivity analysis of multi-ESSs model include the impact of various ESS capacity, peak load, WTG dispatch restriction index in China power system among case study. In addition, the capacity credit of WTG with multi-ESSs were evaluated in this study.

Keywords Renewable energy · Reliability evaluation · Multi-ESSs · Capacity credit

1 Introduction

Since the second and third industrial revolutions, the society experienced an impetuous advancement in technology as well as in economic sectors. The large traditional energy usage causes emissions of carbon, which affects global temperature to rise and form a shortage of fossil resources alongside. Renewable energy resources are abundant and have renewable properties. Therefore, the rational use of renewable energy will be the key to solve future energy shortages and protect the natural environment [1]. WTG has a good prospect of development and practical value. Electricity production is a gradual process. The planning, operation and control of the power grid are based on the principle of "balance between supply and demand." However, distributed generation based on wind turbines and photovoltaic power generation mainly depend on external conditions, which have fluctuations. It is difficult to regular and control them. This may lead to an unbalance between supply and demand. Large scale renewable energy generation connections in the power system will have a serious impact on the stable operation of the power system. To solve this problem, the multi-ESSs, which is system of WTG linked with each ESS, can be installed into the system. When the system is fully supplied, it will store energy and release it when the power system is stationary [2].

The power system reliability is the ability of the power system to continuously provide sufficient and high quality electricity to electricity power consumers. The reliability of power systems can be measured with reliability indicators. These indicators include the probability of failure, the frequency of the failure, and the time period of the failure. In addition, the expected power loss [MW] and expected electrical energy loss [MWh] caused by faults can also be used as indicators of power system reliability [3].

✉ Jaeseok Choi
jschoi@gnu.ac.kr

Jingfeng Zhao
zjf@gnu.ac.kr

Ungjin Oh
vkdlskf@nate.com

Yeonchan Lee
kkng1914@gnu.ac.kr

Joochang Park
jcpark94@gnu.ac.kr

[1] Department of Electrical Engineering, Gyeongsang National University, Jinju, Korea

Probabilistic reliability evaluation of composite power systems including WTG [4] and effect of multi-BESS coordinated WTGs on power system reliability were studied by Prof. Jaeseok Choi (2017) [5]. In addition, the reliability evaluation of a single ESS model use MCS was studied by Dr. Po Hu (2009) [6]. Furthermore, the power system reliability impact of energy storage integration with intelligent operation strategy was studied by Prof. Chanan Singh (2014) [7].

The motive of this paper is to propose a model for the probabilistic reliability assessment of power systems with multi-ESSs installed in wind farms. In order to get the most optimized power system reliability solution, a multi-ESSs optimization operation problem was proposed in coordination with multi-WTGs in this paper. This algorithm is not only suitable for next-generation energy technologies with renewable energy resources, but also applicable to the feasibility and sensitivity analysis of conversion technologies.

2 Probabilistic Reliability Evaluation Method Using Monte Carlo Simulation

The MCS method is a calculation method based on the theoretical methods of probability and statistics. Considering the instability of renewable energy and the inherent uncertainty in the system, use MCS method can obtain the power system reliability coefficient through repeatedly and numerically generating a series of random numbers [8].

2.1 Generation Model

The two-state generator model include operating state (ON) and forced out of service state (OFF) as shown as Fig. 1a. In Fig. 1a, λ and μ are failure rate and repair rate respectively. They are calculated as like as Eqs. (1) and (2) [4].

$$\lambda = \frac{1}{MTTF} \tag{1}$$

$$\mu = \frac{1}{MTTR} \tag{2}$$

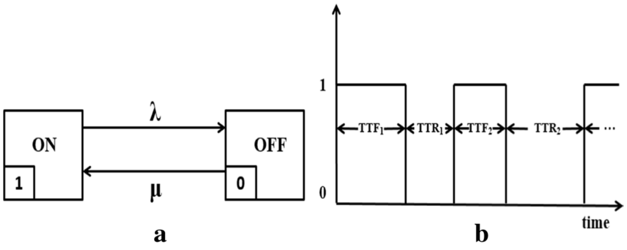

Fig. 1 **a** Two-state generator model; **b** operating cycle of two-state generator model

In the above equations, MTTF is mean time to failure and MTTR means mean time to repair. Sampling values of the time to failure (TTF) and time to repair (TTR) are shown in Fig. 1b. The relationship between TTF, TTR, and MTTF, MTTR can be obtained from the following equations [8].

$$MTTF_i = \sum_{k=1}^{nY_i} TTF_{i,k}/nY_i \tag{3}$$

$$MTTR_i = \sum_{k=1}^{nY_i} TTR_{i,k}/nY_i \tag{4}$$

where $\text{TTF}_{i,k}$ is time to failure of the *i*th generator at *k*th state [h], $\text{TTR}_{i,k}$ is time to repair of the *i*th generator at *k*th state [h]; MTTF_i is mean time to failure of the *i*th generator [h]; MTTR_i is mean time to repair of the *i*th generator [h]; $n\text{Y}_i$ is Total operating years of the *i*th generator [years].

The chronological state transition process for a two-state generation is shown as Fig. 1b. The actual operating time in each generator unit maybe not be the same. So, it is impossible to apply the real operating results in a same time period. A virtual operation scenario for the same time period should be generated as shown as Fig. 2. The time period for each time regions with the MCS method is based on the forced outage rate (FOR) of the two-state model as shown as Eq. (5) [9].

$$FOR_i = \frac{MTTR_i}{MTTF_i + MTTR_i} = \frac{\lambda_i}{\mu_i + \lambda_i} \tag{5}$$

where FOR_i is forced outage rate at *i*th unit; λ_i is failure rate at *i*th unit; μ_i is repair rate at *i*th unit.

From the chronological state transition process for a two-state generation, the operation history cycle for the virtual generators can be calculated by using following equations, Eqs. (6) and (7).

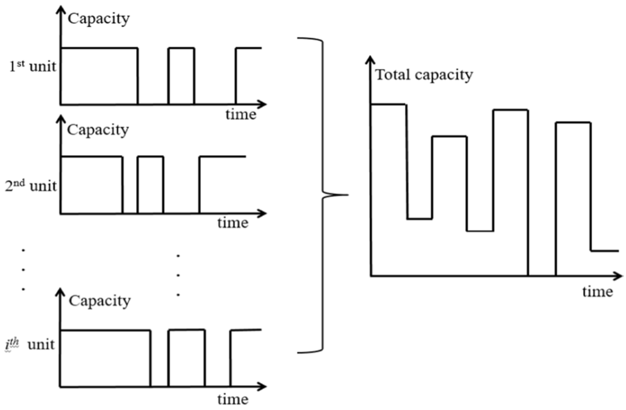

Fig. 2 Available capacity of an example system

$$TTF_{i,k} = -MTTF_i \ln U_k = -\frac{1}{\lambda_i} \ln U_k \tag{6}$$

$$TTR_{i,k} = -MTTR_i \ln U'_k = -\frac{1}{\lambda_i} \ln U'_k \tag{7}$$

There the U_k and U_k’ are the two uniformly distributed random number sequences between [0, 1] at the *k*th state. The total generator capacity in this research can be calculated using following Eq. (8).

$$TG_k = \sum_{i \in NG} G_{i,k} \times ISK_{i,k} \tag{8}$$

$$ISK_{i,k} = \begin{cases} 1 & k \in \Omega_{TTF_i} \\ 0 & k \in \Omega_{TTR_i} \end{cases} \tag{9}$$

where $ISK_{i,k}$ is the *i*th generator probability at *k*th state; TG_k is total generation capacity at the *k*th state [MW]; NG is total generator unit; $G_{i,k}$ is the *i*th generator capacity at the *k*th state [MW]; Ω_{TTFi} is time to failure set at *i*th generator; Ω_{TTRi} is time to repair set at *i*th generator.

In order to see the failure of the power system visually, the chronological load curve can be superimposed on the curve of the system’s available capacity. Therefore, the available capacity of a system with load curve can be got as shown in Fig. 3.

The reliability indices can be calculated using the following equations [10]. First, supply reserve power (SRP) can be calculated using Eq. (10). When the SRP_k is negative, the not served energy (ENS_k) arise. ENS_k can be calculated using Eq. (11) as well. Thus, the reliability index expected energy not supplied (EENS) for a period is shown as Eq. (12).

$$SRP_k = TG_k + TW_k - PD_k \tag{10}$$

$$ENS_k = \begin{cases} SRP_k & SRP < 0 \\ 0 & SRP \geq 0 \end{cases} \tag{11}$$

$$EENS = \sum_{k=1}^{NSS} ENS_k / NY \tag{12}$$

where SRP_k is supply reserve power at *k*th state [MW]; TG_k is total conventional generator capacity at *k*th state [MW]; TW_k is total wind turbine generator capacity at *k*th state [MW]; PD_k is demand power at *k*th state [MW]; NSS is total number of states; NY is the period time in the MCS.

2.2 Wind Turbine Generator (WTG) Model

WTG systems are complex systems and generally include wind turbines, transmissions, generators, converters and corresponding support components, connection components and control components. WTG is an electrical equipment that converts wind resources into mechanical energy, thereby converting mechanical energy to electrical energy. The methodology for WTG model in this study is divided into two parts. Including the wind speed part and wind energy conversion system power generation part. The generation of hourly wind speed over a sufficiently long period of time is given site in this paper. The wind speed plays an important role in WTG output, there typical power curve of a WTG according to changing wind speed is shown in Fig. 4 [11].

As mentioned above, the WTG output (P_W) depends on the wind speed. The P_W according to changing wind speed can be calculated as follow equations.

$$P_W = 0, \quad 0 \leq V \leq V_{ci} \tag{13}$$

$$P_W = P_R\left(A + B \times V + C \times V^2\right), \quad V_{ci} \leq V \leq V_r \tag{14}$$

$$P_W = P_R, \quad V_r \leq V \leq V_{co} \tag{15}$$

$$P_W = 0, \quad V \geq V_{co} \tag{16}$$

The constants A, B, and C in Eq. (14) are depending on the cut-in wind speed (V_{ci}), rated wind speed (V_r) and cut out wind speed (V_{co}) which can be determined as follow equations [12].

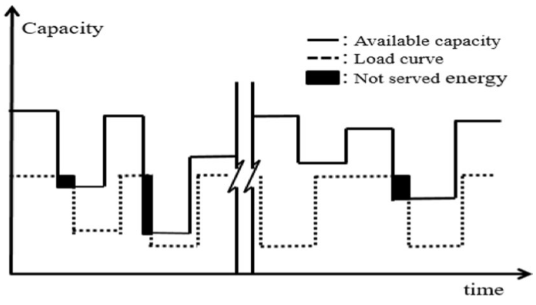

Fig. 3 Available capacity of a system with the load curve

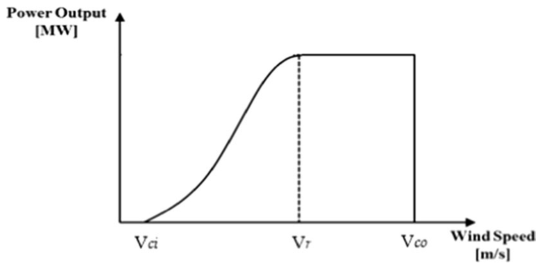

Fig. 4 WTG output curve

$$A = \frac{1}{(V_{ci} - V_r)^2}\left[V_{ci}(V_{ci} + V_r) - 4(V_{ci}V_r)\left(\frac{V_{ci} + V_r}{2V_r}\right)^3\right] \tag{17}$$

$$B = \frac{1}{(V_{ci} - V_r)^2}\left[4(V_{ci}V_r)\left(\frac{V_{ci} + V_r}{2V_r}\right)^3 - \left(3V_{ci} + V_r\right)\right] \tag{18}$$

$$C = \frac{1}{(V_{ci} - V_r)^2}\left[2 - 4\left(\frac{V_{ci} + V_r}{2V_r}\right)^3\right] \tag{19}$$

Different places usually have different wind resources and the wind speed will not be the same. Even in the same area, the wind speed will change with the season and time. However, by observing the distribution of wind speed over a number of years in different regions, wind speeds in different regions will exhibit a similar Weibull probability distribution with a similar normal distribution. Combined with the wind output model mentioned above, the expected WTG output can be calculated using Eq. (20) [12].

$$EP_{WTG_{k,t}} = \sum_{i \in \rho_{kt}} \left(PB_{swi} \times P_{swi}\right) \tag{20}$$

where $\mathrm{EP}_{WTGk,t}$ is WTG expected output at time *t* of *k*th wind farm [MW]; P_{SWi} is WTG expected output when the wind speed is SW_i [MW]; PB_{SWi} is probability when the wind speed is SW_i; ρ_{kt} is the set of wind speeds on wind farm *k*th in a certain time *t*.

2.3 Multi-ESSs Model

This paper aims to develop a multi-ESSs model. This model requires each ESS to be connected to each wind farm to perform charging mode and discharging mode by using an appropriate control method. The basic model include multi-WTGs coordinated with multi-ESSs in power system is shown in Fig. 5.

Where TG_{ci} is the *i*th conventional generator (CG) capacity [MW]; TG_{wi} is the *i*th WTG capacity [MW]; SG_{wi} is surplus output of *i*th WTG [MW]; q_i is forced outage rate of *i*th CG; X% is percentage of a wind power dispatch restriction to supply load [pu]; X_i% is percentage of the *i*th WTG dispatch restriction to supply load [pu].

In the multi-ESSs model, the output WTG and ESS using to supply the load must obey the following rules [13].

WTG is using to supply the system load directly. If the wind resources are rich, the wind power is sufficient to supply demand. As a result, some of the surplus wind power can be stored in ESS. Once the wind speed is known, the total output of WTG can be calculated by using the WTG output curve. Then, use the wind power dispatch restriction parameter X% which is mentioned in the multi-ESSs model to calculate the surplus output of WTG ($\mathrm{SG}_{wi,k}$) as shown as Eq. (21). By the way, surplus output of CG ($\mathrm{SG}_{ci,k}$) can be calculated use the total generator capacity of the conventional generating units minus the (1 − X%) total load as shown as Eq. (22).

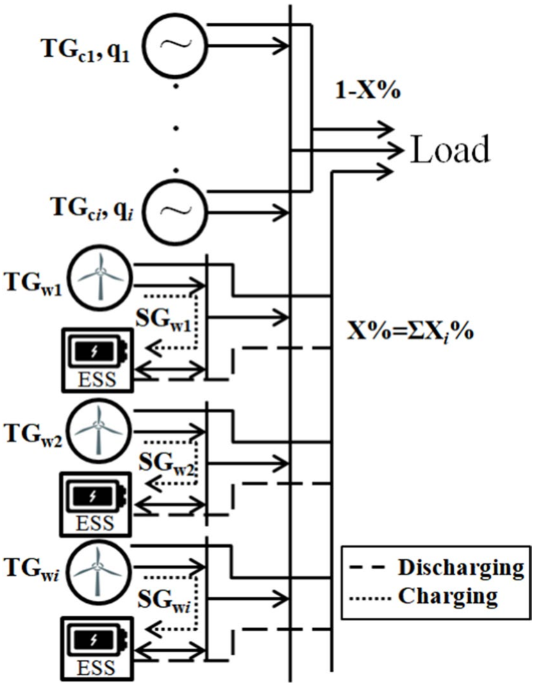

Fig. 5 Complete system with multi-ESSs model

$$SG_{wk} = \sum TG_{wi,k} - X_i\% \times L_k = \sum SG_{wi,k} \tag{21}$$

$$SG_{ck} = \sum TG_{ci,k} - (1 - X_i\%) \times L_k = \sum SG_{ci,k} \tag{22}$$

where SG_{wk} is total surplus output of the WTG at the *k*th state [MW]; $\mathrm{SG}_{ci,k}$ is total surplus output of the CG at the *k*th state [MW], $\mathrm{TG}_{wi,k}$ is the *i*th WTG capacity at the *k*th state [MW]; $\mathrm{TG}_{ci,k}$ is the *i*th conventional generator capacity at the *k*th state [MW]; $\mathrm{SG}_{wi,k}$ is surplus output of the *i*th WTG at the *k*th state [MW]; $\mathrm{SG}_{wi,k}$ is surplus output of the *i*th WTG at the *k*th state [MW]; L_k is load at the *k*th state [MW]; X_i% is percentage of the *i*th WTG dispatch restriction to supply load [pu].

The energy storage time series for charging mode $\mathrm{ES}_{i,k}$, and the energy storage time series for discharging mode $\mathrm{TG}_{Di,k}$ can be calculated in different conditions by using the following equations.

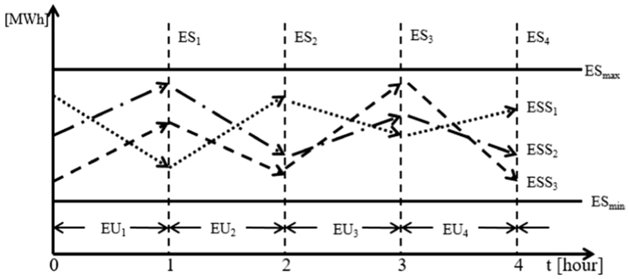

Fig. 6 ESS state of charge transition feature

$$ES_{i,k+1} = \begin{cases} ES_{i,k} + SG_{wi,k} \times t_k & SG_{wi,k} \geq 0,\ SG_{ci,k} \geq 0 \\ ES_{i,k} + SG_{ci,k} \times t_k & SG_{wi,k} \geq 0,\ SG_{ci,k} < 0 \\ ES_{i,k} & SG_{wi,k} < 0,\ (SG_{wi,k} + SG_{ci,k}) \geq 0 \\ ES_{i,k} + (SG_{wi,k} + SG_{ci,k}) \times t_k & SG_{wi,k} < 0,\ (SG_{wi,k} + SG_{ci,k}) \leq 0 \end{cases} \tag{23}$$

$$TG_{Di,k} = \begin{cases} 0 & SG_{wi,k} \geq 0,\ SG_{ci,k} \geq 0 \\ -SG_{ci,k} \times t_k & SG_{wi,k} \geq 0,\ SG_{ci,k} < 0 \\ 0 & SG_{wi,k} < 0,\ (SG_{wi,k} + SG_{ci,k}) \geq 0 \\ -(SG_{wi,k} + SG_{ci,k}) \times t_k & SG_{wi,k} < 0,\ (SG_{wi,k} + SG_{ci,k}) < 0 \end{cases} \tag{24}$$

The ESS state of charge transition feature is shown as Fig. 6 [14]. If the SG$_{wi,k}$ is positive, the ESS should be charged. If the SG$_{ci,k}$ is negative the ESS should be discharged. Therefore the control value of energy for ESS, EU$_{i,k}$ is proposed in this paper. In addition the state of energy ES$_{i,k}$ stored in the ESS is limited by a maximum value and minimum value as shown in following equations.

$$ES_{\min,i} \leq ES_{i,k} + EU_{i,k} \leq ES_{\max,i} \tag{25}$$

$$ES_{i,k} = ES_{i,k-1} + EU_{i,k} \tag{26}$$

$$ES_{\min,i} \leq ES_{i,k} \leq ES_{\max,i} \tag{27}$$

2.4 Multi-ESSs Operating Rule

The multi-ESSs model used in the power system aims to ensure reliable supply from each uncontrollable output of WTG. Therefore, the multi-ESSs operation rules is important to be determined as discharging mode and charging mode. As mentioned above, SG$_{wk}$ is a surplus output of WTG at *k*th state and SG$_{ck}$ is surplus output of CG at *k*th state. There is new parameter SG$_k$, shown as Eq. (28).

$$SG_k = SG_{wk} + SG_{ck} \tag{28}$$

As for operating rules, the proposed multi-ESSs model used the charging and discharging conditions as shown in Table 1.

As for discharging modes (II, IV), in the system with WTG connected multi-ESSs, if the total output of the existing conventional generators are less than (1 − X%) × L$_k$, ESS releases energy, as it is the discharge mode operates. In addition, if the total output of the existing conventional generators are less than (1 − X%) × L$_k$, and, at the same time the WTG's maximum permissible energy output is more than X% × L$_k$, in this time the ESS also discharge. In the power system with multi-ESSs, if only several ESSs used to supply the load can satisfy the demand, then the rest ESSs can be charged at the same time. However, if the power system only installed single ESS, it cannot operate charging mode at the same time with discharging mode. This is the reason why use the mark (★) in Table 1. As for charging mode (I), when the WTG's maximum permissible energy output is more than X% × L$_k$, at the same time the total output of WTG's maximum permissible energy output and the total output of the existing conventional generators are more than (1 − X%) × L$_k$, the ESS will save energy.

2.5 Reliability Evaluation Indices Calculation Method

In this study, a probabilistic method based on MCS is used in this paper through a simulation by repeatedly and numerically generating a series of random numbers. The reliability indices are calculated by summing and averaging the value of LOLE and EENS for every case. In addition, the energy index of reliability (EIR) is defined as follows [15].

(1) Loss of Load Expectation (LOLE) [Hrs/yr]

Table 1 Charging and discharging rules

Mode	SG$_{wk}$	SG$_{ck}$	SG$_k$	Charge	Discharge
I	+	+	+	○	×
II	+	−	+ (−)	★	○
III	−	+	+	×	×
IV	−	−	−	×	○

LOLE represents the average hours that the load value is expected to exceed the available system capacity in a time period t_k.

$$LOLE = \frac{1}{NY} \sum_{k \in \Omega_D} t_k \tag{29}$$

where NY is simulation years; Ω_D is a set of discharge modes.

(2) Expected Energy not Served (EENS) [MWh/yr]

When the power supply of the power system is less than the load demand, the shortage electricity of the power system can be defined as EENS. EENS can be obtained by the Eq. (30).

$$EENS = \frac{1}{NY} \sum_{k \in \Omega_D} (TG_{Dk} + EU_k) \tag{30}$$

where TG_{Dk} is discharge energy indispensable for eliminating any lack of supply for loads [MWh]; EU_k is discharging control energy [MWh].

(3) Energy Index of Reliability (EIR) [pu]

$$EIR = 1 - \frac{EENS}{TDE} \tag{31}$$

where TDE is total demand energy [MWh].

2.6 Effective Load Carrying Capability (ELCC) and Capacity Credit (C.C.)

Using multi-ESSs model in a power system with distributed power sources can reduce the probability of insufficient power supply, thereby improving the reliability of the system. However, the actual reliable capacity of wind power will be less than its installed capacity. This chapter introduces the concept of actual reliable capacity of WTG and ESS. The capacity credit (C.C.) of the WTG is the ratio of its trusted capacity to its installed capacity [16].

(1) Effective load carrying capability (ELCC) calculation method

ELCC represents as "under the same stochastic target risk level, the ability of power system with supply load changes before and after expansion". The concept of ELCC as shown as Fig. 7 [16].

There, $LOLE^*$ is the same stochastic target risk level can be understood as same level of LOLE. The ELCC can be calculated using following equation.

$$ELCC = PL_{ES}^{LOLE^*} - PL_{OS}^{LOLE^*} \tag{32}$$

where $PL^{LOLE^*}{}_{ES}$ is peak load of expanded system when the system LOLE is $LOLE^*$. $PL^{LOLE^*}{}_{OS}$ is peak load of original system when the system LOLE is $LOLE^*$.

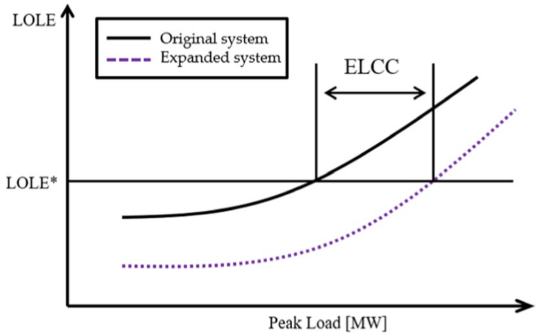

Fig. 7 Definition of ELCC

Table 2 Generator data of China power system in 2016

Type	Capacity [MW]	Units
Coal	942,590	1969
Gas	70,080	152
Nuclear	33,640	37
Wind	148,680	3
Total	1,194,990	2161

(2) Capacity credit (C.C.) calculation method

C.C. is not only related to the expanded capacity in the power system, but also related to the economics of renewable energy generation. It is used as the index for valuation of renewable energy, which has much volatility. C_A is total capacity of new generation.

$$C.C. = \frac{ELCC}{C_A} \times 100\ [\%] \tag{33}$$

3 Case Study

The proposed method is applied to a power system of China-sized sample. According to the method mentioned above, using the input data from the similar China power system make a reliability evaluation for the power system. 1.36 billion people live within the 9,634,060 [km^2] area in China. In 2016, power system installed capacity in China is shown in Table 2.

In this case study, WTG in China's power system are integrated into three wind farms. Regionally divided into western wind area (WWA), eastern wind area (EWA) and southern wind area (SWA) shown as Fig. 8.

There the WTG installed capacity in each wind areas shown as Table 3. In this table, the characteristic data

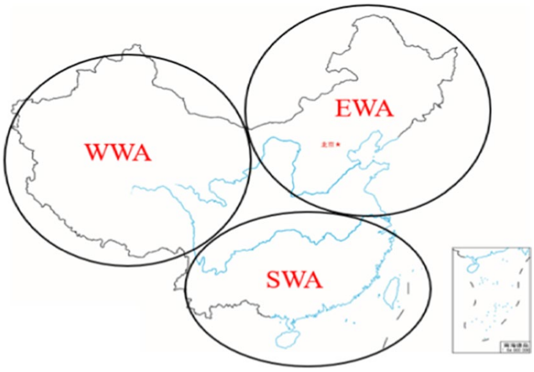

Fig. 8 Regional wind farms in China

Table 3 WTG characteristic data of wind areas in China

Wind area	WWA	EWA	SWA
WTG capacity [MW]	73,920	47,500	27,260
Cut-in speed (V_{ci})	5 m/s	5 m/s	5 m/s
Rated speed (V_r)	10 m/s	10 m/s	10 m/s
Cut-out speed (V_{co})	25 m/s	25 m/s	25 m/s
Average speed	5.7 m/s	5.7 m/s	5.7 m/s

include cut in wind speed, rated wind speed, cut out wind speed and average wind speed are also mentioned.

3.1 Basic Model of Reliability Evaluation

This paper aims to find the best way to improve the reliability of power system. That is using 3 kinds of different model systems for the following simulation (Fig. 9).

In System C, the ESS specifications data with maximum ESS capacity is shown in Table 4.

3.2 Basic Analysis of the Influence from Peak Load on System Reliability

After rapidly develop of China's electrical industry over the last decade. The China's electricity supply condition has been changed from a shortage electricity to an oversupply phenomenon. By the way, the imbalances in supply and demand condition are likely continue for the next decade.

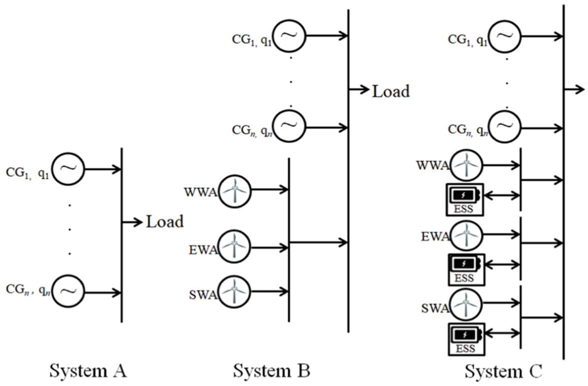

Fig. 9 Three kinds of power systems in this paper

Table 5 shows the reliability evaluation result of variation of LOLE, EENS and EIR of the model system according to changing of peak load in every model system. Max. ESS capacity in each wind farm in System C are shown as Table 4. Actually, China power system has already over capacity, and peak load is 980 [GW], at this point the reliability index is hardly change. In order to continue the research, choose the peak load as 1050 [GW] to continue the follow simulation (Figs. 10, 11).

Above figures shows the reliability evaluation result of each system. There the peak load in these systems are 1050 [GW]. And the Max. ESS capacity in each wind area of systems are given in Table 6, System C is the most reliable.

3.3 Basic Analysis on the Impact of ESS Capacity on Reliability

In order to research the influence of ESS installed capacity on system reliability, 7 cases were proposed as shown in follow Table 7.

Figure 12 shows the variation of LOLE and EENS of the model system according to changing of Max. ESS capacity in the 6 cases. It can easily see when the curve comes to Case D, the LOLE and EENS is decreased slowly. Compared Case E with Case F, the LOLE is hardly saturated. Therefore, in view point of reliability, it can be determined that optimal capacity of ESS is Case E (LOLE = 0.16 [Hrs/yr]).

Table 4 Multi-ESSs specifications in System C

	Max. capacity [MWh]	Min. capacity [MWh]	Duration for charge or discharge (h)	X% [pu]	Initial SOC of ESS [MWh]
WWA	18,480	100	1	0.1	200
EWA	11,875	100	1	0.1	200
SWA	6815	100	1	0.1	200

Table 5 Reliability evaluation result in all of the systems

Peak load [GW]	System	LOLE [Hrs/yr]	EENS [MWh/yr]	EIR [pu]
925	A	0	0	1
	B	0	0	1
	C	0	0	1
950	A	0.08	825.6	0.999999853
	B	0.02	58.4	0.999999999
	C	0	0	1
975	A	0.14	3350.3	0.999999439
	B	0.08	1341.3	0.999999775
	C	0	0	1
1000	A	0.54	10,097.4	0.999998351
	B	0.2	4147.7	0.999999323
	C	0.08	2365	0.9999996137
1025	A	2.56	41,836.1	0.999993333
	B	0.8	13,684.9	0.999997819
	C	0.28	7565.9	0.9999987942
1050	A	8.16	164,979	0.999974333
	B	3.08	48,474.2	0.999990903
	C	1.98	40,613.2	0.9999936816
1075	A	17.74	470,426.5	0.999928515
	B	8.68	190,633.4	0.999971032
	C	6.96	160,012.5	0.9999756850
1100	A	31.98	1,045,319.5	0.999844767
	B	17.64	498,600.9	0.999925956
	C	14.92	450,685.1	0.9999330717

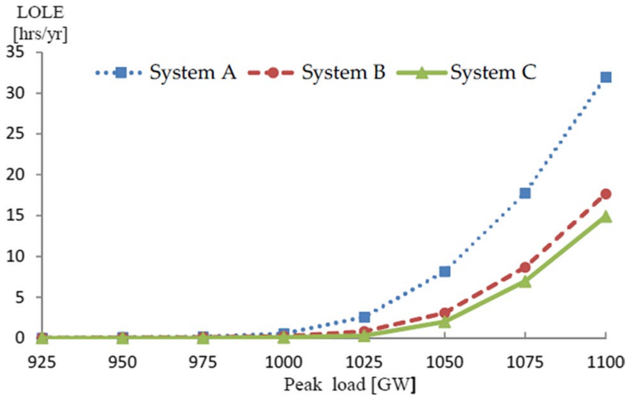

Fig. 10 LOLE with variation results under varying peak load

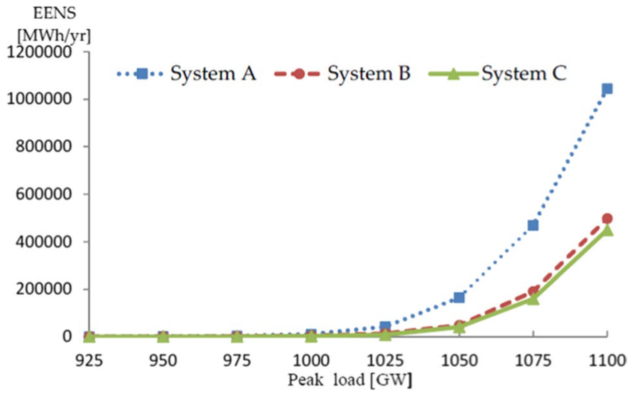

Fig. 11 EENS with variation results under varying peak load

3.4 Basic Analysis of WTG Dispatch Restriction to Supply Load (X% [pu])

4 cases are created to compare the variation of reliability index with the change of ESS capacity and the percentage of wind power dispatch restriction to supply load (X% [pu]). Got the result in each case as shown in Table 8.

Table 6 Reliability evaluation result for all systems

	System A	System B	System C
LOLE [Hrs/yr]	8.16	3.08	1.98
EENS [MWh/yr]	164,979	48,474.2	40,163.2
EIR [pu]	0.999974333	0.999990903	0.999996816

Table 7 Max. ESS characteristic data of cases

Cases	Max. ESS capacity [MWh]			
	WWA	EWA	SWA	Total
A	18,480	11,875	6,815	37,170
B	36,960	23,750	13,630	74,340
C	73,920	47,500	27,260	148,680
D	110,880	71,250	40,890	223,020
E	147,840	95,000	54,520	297,360
F	184,800	118,750	68,150	371,700
G	221,760	142,500	81,780	446,040

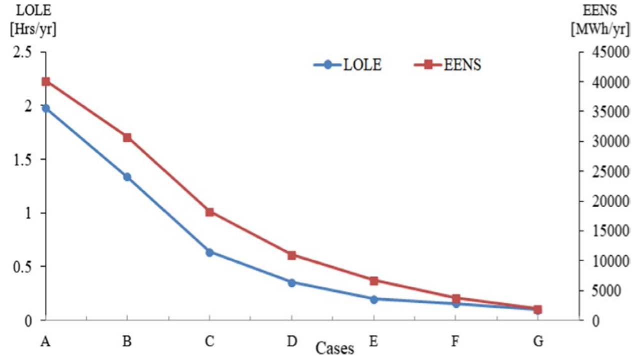

Fig. 12 Variation of reliability index of cases according to changing of ESS capacity

- Case 1: Without ESS
- Case 2: ESS capacity are WWA: 36,960 MW, EWA: 23,750 MW, SWA: 13,630 MW.
- Case 3: ESS capacity are WWA: 73,920 MW, EWA: 47,500 MW, SWA: 27,260 MW.
- Case 4: ESS capacity are WWA: 184,800 MW, EWA: 118,750 MW, SWA: 68,150 MW.

Results of system reliability changes as X% and Max. ESS Capacity changes as shown in Fig. 13. From this figure, after the curve arrived at the point X% = 0.3 [pu]. All of the cases have the same LOLE. It means added ESS or not is no influence for power system reliability, the ESS is not work. At the point X% = 0.1 [pu], WTG and multi-ESSs works flexible, efficient, every case has lowest LOLE. Therefore, the best reliability case can be Case 4 with the X% = 0.1 [pu].

Table 8 Reliability evaluation result according to changing of X% [pu]

X% [pu]	Case	LOLE [Hrs/yr]	EENS [MWh/yr]	EIR [pu]
0	1	8.16	164,979	0.999974333
	2	3	61,932.1	0.999990367
	3	2.52	55,478.1	0.99991369
	4	2.74	63,237.5	0.999990102
0.1	1	3.08	58,474.2	0.999990903
	2	1.34	30,753.1	0.999995216
	3	0.64	18,273.3	0.999997157
	4	0.2	6703.2	0.999998957
0.2	1	3.08	58,474.2	0.999990903
	2	2.68	52,366.9	0.999991853
	3	2.68	52,366.9	0.999991853
	4	2.68	52,366.9	0.999991853
0.3	1	3.08	58,474.2	0.999990903
	2	3.08	58,468.2	0.999990904
	3	3.08	58,468.2	0.999990904
	4	3.08	58,468.2	0.999990904
0.4	1	3.08	58,474.2	0.999990904
	2	3.08	58,468.2	0.999990904
	3	3.08	58,468.2	0.999990904
	4	3.08	58,468.2	0.999990904
0.5	1	3.08	58,474.2	0.999990904
	2	3.08	58,468.2	0.999990904
	3	3.08	58,468.2	0.999990904
	4	3.08	58,468.2	0.999990904

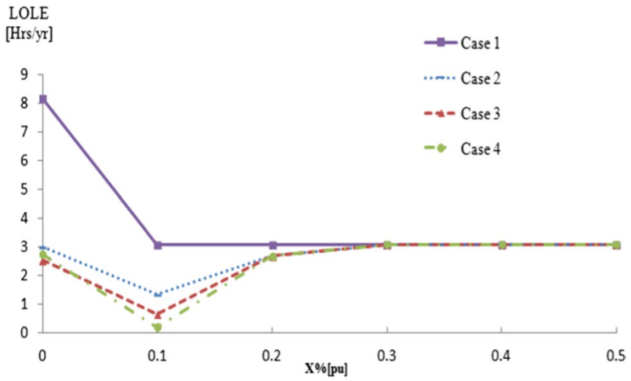

Fig. 13 Results of system reliability changes as X% and Max. ESS Capacity changes

3.5 Effective Load Carrying Capability [ELCC] and Capacity Credit [C.C.] Calculation

Aimed to calculate the ELCC, there are 3 systems shown as Fig. 9 used in this part. Set a same LOLE level in each system and find the value of peak load. The input data in the model systems is shown in Table 9.

China power system's LOLE is around 8 [Hrs/yr] in 2016, Fig. 14 shows the variation of LOLE of the model systems when the peak load is changed used for calculating ELCC. It is set to the LOLE equal 8 [Hrs/yr] and find the value of peak load. By finding the result for the

Table 9 Input data of model systems

System	CG capacity [MW]	WTG capacity [MW] (Max. ESS capacity [MWh])		
		WWA	EWA	SWA
A	1,046,310	0 (0)	0 (0)	0 (0)
B	1,046,310	73,920 (0)	47,500 (0)	27,260 (0)
C	1,046,310	73,920 (18,480)	47,500 (11,875)	27,260 (6815)

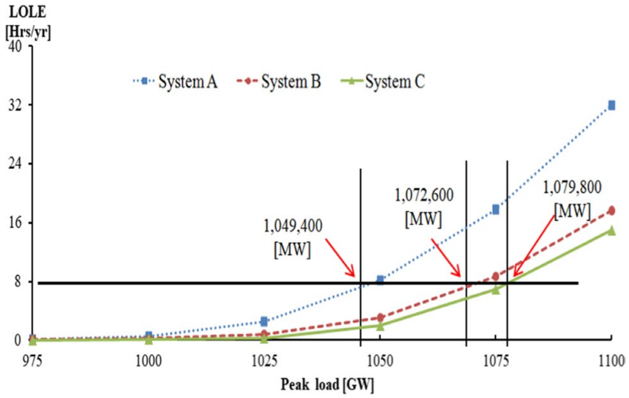

Fig. 14 Reliability indices in advanced systems

peak load corresponding to each system's LOLE equal to 8 [Hrs/yr], calculate the ELCC and C.C. shown as follow.

(1) ELCC and C.C. calculation of system expanded WTGs

As for System B, three wind farms were added based on System A, Thereby, the ELCC and C.C. of expanded WTGs can be calculated as:

$$ELCC_{WTG} = 1{,}072{,}600 - 1{,}049{,}400 = 23{,}200\ [\text{MW}]$$

$$C.C._{\cdot WTG} = \frac{23{,}200}{148{,}680} \times 100\% = 15.6\%$$

(2) ELCC and C.C. calculation of system expanded ESSs

As for System C, three ESSs were added based on System B. Thus, the ELCC and C.C. of expanded ESS can be calculated as:

$$ELCC_{ESS} = 1{,}079{,}800 - 1{,}072{,}600 = 7200\ [\text{MW}]$$

$$C.C._{\cdot ESS} = \frac{7200}{37{,}170} \times 100\% = 19.37\%$$

(3) ELCC and C.C. calculation of system added WTGs and ESSs

As for System C, three wind farms and multi-ESSs are added based on System A. Therefore, the ELCC and C.C. of expanded WTGs and multi-ESS can be calculated as:

$$ELCC_{ESS+WTG} = 1{,}079{,}800 - 1{,}049{,}400 = 30{,}400\ [\text{MW}]$$

$$C.C._{\cdot ESS+WTG} = \frac{30{,}400}{185{,}850} \times 100\% = 16.36\%$$

Table 10 Calculation result of ELCC and C.C.

	ELCC [MW]	C.C. (%)
WTG	23,200	15.6
ESS	7200	19.37
WTG + ESS	30,400	16.36

After expanded WTGs and multi-ESSs in the power system, the ELCC has been increased from 23,200 to 30,400 [MW]. In addition, the C.C. has been increased. This means the multi-ESSs is helpful to increase the power system reliability (Table 10).

4 Conclusion

Sustainable energy system has been emphasized nowadays and many countries in the world will develop renewable energy as it can ease the contradiction of energy supply and address climate change. Thus, the energy structure will undergo major changes and the vast majority of the clean energy use of renewable energy will increasingly replace fossil energy for power generation. Therefore, how to effectively use distributed renewable energy to generate electricity without affecting the reliability of the power system is the primary task in the whole world.

First of all, multi-ESSs can maintain supply and demand balance by compensating for the uncertainty of power generation output from renewable energy. Secondly, the results of this research can provide reference opinions in the efficient and reliable application of distributed renewable energy in power systems.

Therefore, in order to avoid the uncertainty of WTG output and power fluctuations affecting the reliability of power systems, the application of multi-ESSs is a good method to ensure the reliability of power systems.

In this research, the reliability of a power system involving WTG and multi-ESSs can be evaluated using a basic model and algorithm. By using the proposed model, the reliability analysis of WTG with multi-ESSs can be obtained. Suitable capacity of WTG and multi-ESSs can be determined and used efficiently for a sensitivity analysis from the result. This research is helpful for future power system expansion planning.

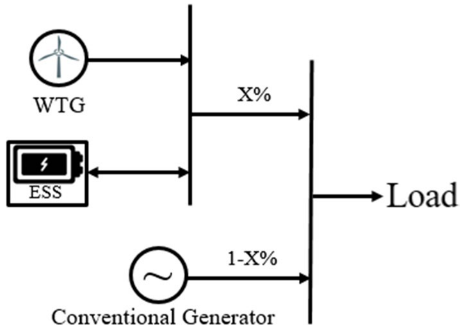

Fig. 15 An example system include CG and WTG with ESS

Appendix

A basic theory of the WTG cooperated with ESS dispatch restriction to supply load indices (X% [pu]) was introduced in this appendix.

The applying of a large amount of wind energy to the grid may cause the reliability of the whole power system to be greatly affected. The affect can be caused by the power demand and power supply do not coincide at the same time. Thus, using ESS can be help to improve utilizing the uncontrollable WTG.

However, if the WTG with CG supply energy to the load directly, there will have two different conditions. When the WTG is small, WTG can be serving to the load of the system, in this time, the system can utilizing all of the output power from WTG. When the WTG is large, it will be difficult to absorb all of WTG while ensuring the stability of the system. And also, even used ESS together with the large amount of WTG, the ESS operation is not flexible in this condition. Therefore, the WTG dispatch restriction to serve the load X% [pu] was purposed.

Figure 15 shows an example system. After setting the WTG dispatch restriction to supply the load (X%) [pu], the WTG only need to supply the X% of hourly load. CG will serve (1 – X%) of the hourly load. If the total WTG hourly output is over the X% of hourly load, the surplus WTG output can be stored to the ESS. And the ESS will discharge when the total hourly WTG output is not reached the X% of the hourly system load. Suit value of WTG dispatch restriction to supply load indices (X% [pu]) can help improve the stability of the system and the flexible, efficient operation of the ESS.

Acknowledgements This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy. (No. 20194030202430).

References

1. Zhao J, Choi W, Choi J (2017) The trend of power system in China. In: Proceeding of 2017 KIEE autumn conference, Gwangju, Korea, Nov
2. Zhao J, Oh U, Cha J, Choi J (2018) Probabilistic reliability evaluation on a power system considering wind energy with energy storage systems in China. In: Proceeding of 10th IFAC symposium on control of power and energy systems, Tokyo, Sept
3. Choi J (2013) Power system reliability evaluation engineering. G&U Press, Washington, DC
4. Choi J, Park J, Cho K, Oh T, Shahidehpour M (2010) Probabilistic reliability evaluation of composite power systems including wind turbine generators. In: Proceeding of 2010 IEEE 11th international conference on probabilistic methods applied to power systems, Singapore, June
5. Oh U, Lee Y, Choi J, Lim J, Cha J (2017) Effect of multi-BESS coordinated WTGs on power system reliability. In: Proceedings of 2017 IEEE Power & Energy Society general meeting, Chicago, July
6. Hu P, Karki R, Billinton R (2009) Reliability evaluation of generating systems containing wind power and energy storage. IET Gener Transm Distrib 3(8):783–791
7. Xu Y, Singh C (2014) Power system reliability impact of energy storage integration with intelligent operation strategy. IEEE Trans Smart Grid 5(2):1129–1137
8. Oh U, Lee Y, Choi J, Karki R (2020) Reliability evaluation of power system considering wind generators coordinated with multi-energy storage systems. IET Gener Transm Distrib 14(5):786–796
9. Billinton R, Li W (1994) Reliability assessment of electric power systems using Monte Carlo methods. Plenum Press, New York
10. Oh U, Choi J, Kim H (2016) Reliability contribution function considering wind turbine generators and battery energy storage system in power system. In: Proceeding of IFAC workshop on control of transmission and distribution smart grids proceeding, Prague, Oct
11. Karki R, Hu P, Billinton R (2006) A simplified wind power generation model for reliability evaluation. IEEE Trans Energy Convers 21(2):533–540
12. Seguro JV, Lambert TW (2000) Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. J Wind Eng Ind Aerodyn 85(1):75–84
13. Oh U, Lee Y, Lim J, Choi J, Yoon Y, Chang B, Cho S (2015) Reliability evaluation with wind turbine generators and an energy storage system for the Jeju Island Power System. Trans Korean Inst Electr Eng 64(1):1–7
14. Oh U, Lee Y, Choi J, Yoon Y, Chang B, Cha J (2016) Development of reliability contribution function of power system including wind turbine generators combined with battery energy storage system. Trans Korean Inst Electr Eng 65(3):371–381
15. Choi J, Lim J, Lee KY (2013) DSM considered probabilistic reliability evaluation and an information system for power systems including wind turbine generators. IEEE Trans Smart Grid 4(1):425–432
16. Garver LL (1966) Effective load carrying capability of generating units. IEEE Trans Power Appar Syst 85(8):910–919

Jingfeng Zhao He was born in Jining, China, in 1994. He received the B. Sc. degree from Qingdao Agricultural University, Qingdao, China. He received his M.Sc. degree from Gyeongsang National University, Jinju, Korea in 2018. Now, he is studying for a Ph.D course at power system lab, Department of Electrical Engineering, Gyeongsang National University, Jinju, Korea. His research interests include renewable energy generation, energy storage system and microgrid.

Ungjin Oh He was born in Jinju, Korea in 1985. He received the B.Sc. and M.Sc degree from Gyeongsang National University in 2013 and 2016 respectively. His research interests include reliability evaluation of power systems under renewable energy conditions. Now, he is studying as Ph.D student in Gyeongsang National University, Korea.

Yeonchan Lee He was born in Gosung, Korea in 1987. He received the B.Sc., and M.Sc., degree from Gyeongsang National University in 2013 and 2015 respectively. His research interest includes transmission expansion planning using reliability evaluation of power systems. Now, he is studying as Ph.D., student in Gyeongsang National University, Korea.

Joochang Park He was born in Changwon, South Korea in 1994. His research interest include the reliability and resilience of the power system in preparation for energy transition. He received the B.Sc. degree in Electrical Engineering from Gyeongsang National University, Jinju, in Feb. 2019. Currently, he is studying M.Sc. degree at the same university.

Jaeseok Choi He was born in Kyeongju, Korea, in 1958. He received the B.Sc., M.Sc., and Ph.D. degrees from Korea University, Seoul. Since 1991, he has been on the faculty of Gyeongsang National University, Jinju, Korea, where he is a professor. He was a visiting professor at Cornell University, Ithaca, NY, USA, in 2004. He is also adjunct professor at IIT, IL, USA since 2007. His research interests include fuzzy applications, probabilistic production cost simulation, reliability.