

A Unified Analysis of the Impacts of Stochasticity and Low Inertia of Wind Generation

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Abstract—This paper proposes a new method to model wind generation in power system reliability evaluation that not only considers the uncertainty of wind speed and mechanical failures of wind turbines but also includes the impacts of wind's low inertia property. Due to the stochasticity and low inertia of wind generation, power system stability and reliability are significantly affected. When wind generators are integrated into the grid, a strategy to ensure the system stability is that wind generators are required to operate at a lower level than their maximum available output power. The effect of this requirement is that not all of the available wind power will be used in the system, which in turn affects the contribution of wind generation in power system availability. The proposed model is implemented using Monte Carlo methods. For every system state, the maximum integrated amount of wind power is determined based on frequency regulation requirements. Then, this amount of power is used along with the stochastic model of wind speed in the reliability modeling. The proposed method is demonstrated on the IEEE RTS system. Power system reliability with and without considering the impacts of wind stochasticity and low inertia are compared to show the effectiveness of the proposed method.

Index Terms—Wind generation, frequency regulation, stochasticity, inertia, penetration limit.

I. INTRODUCTION

Due to environmental concerns and growing demand for electricity, the need for additional renewable energy resources has been increasing. Wind energy has proved to be one of the most convenient sources, offering a relatively high capacity and competitive cost, compared to conventional energy sources. Despite environmental and cost advantages, the high penetration level of such intermittent sources negatively affects the stability and reliability of the main grid.

The modeling of wind generation in power system reliability has been investigated by both analytical and simulation approaches. However, explicitly modeling of the impacts of wind speed stochasticity and low/no inertia of wind turbines in power system reliability evaluation has not been reported. As a variable and low inertia source of power, wind generation causes technical challenges such as the generation reserve requirement, frequency deviation, transmission violation [1]–

[6] and voltage instability [7]–[9]. The reduction in frequency response due to an increase of variable generation has been reported by The North American Electric Reliability Corporation (NERC), Electric Reliability Council of Texas (ERCOT) and Western Interconnect (WECC) [10]–[13]. Hydro-Québec TransÉnergie (HQT) is dealing with this problem by requiring their wind power plants to be equipped with an inertia emulation system [14]. These challenges inhibit the penetration level of wind generation. Only the portion of wind generation that provides sufficient conditions to ensure system stability should be deployed. Therefore, the availability of wind generation in power system reliability modeling must be evaluated considering stability requirements. In this paper, the reliability modeling of wind generation that considers the impacts of wind stochasticity and low inertia is investigated. Due to the system stability requirement, the reliability model of wind farms has to be modified. The modification is made based on the following two criteria:

- The wind generators are to operate below their available output power to ensure that they have ability to provide reserve for frequency regulation [15], [16].
- The wind generation has low inertia, which negatively affects the stability of system [17]. Therefore, the wind penetration is limited to ensure the system stability.

Since not all of the available output power of wind generation can be deployed in the system, the reliability of the main grid is affected.

The remainder of this paper is organized as follows. Section II explains the model of wind turbine output and the impacts of wind stochasticity and low inertia. Reliability assessment using Monte Carlo method is presented in Section III. The simulation results using Monte Carlo methods comparing the models with and without considering the impacts of wind stochasticity and low inertia are presented in section IV. In this section, some observations are also included to clarify the salient aspects of the contribution. Finally, section V provides some concluding remarks on the work presented.

II. RELIABILITY OF WIND GENERATION CONSIDERING THE IMPACTS OF UNCERTAINTY AND LOW INERTIA

In this section, a wind generation output model and the impacts of wind stochasticity and low inertia are presented.

A. Modeling of wind turbine output

The output of wind turbine depends on two factors: wind speed and turbine availability. There are several ways to present wind speed model in the literature such as the Weibull distribution model [18], ARMA model [19] or using the real data of measured wind speed in a specific location [20]. The non-linear relationship between wind output and wind speed is shown in equation (1) [21].

$$P_w = \begin{cases} 0 & \text{if } 0 \leq SW_t \leq V_{ci} \\ (A + B \times SW_t + C \times SW_t^2) P_r & \text{if } V_{ci} < SW_t \leq V_r \\ P_r & \text{if } V_r < SW_t \leq V_{co} \\ 0 & \text{if } V_{co} < SW_t \end{cases} \quad (1)$$

where V_{ci} , V_{co} , V_r , SW_t , P_r are the wind turbine's cut-in, cut-out, rated, real speed and rated power, respectively. The constants A, B, C are as follows [22]:

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

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

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

B. Modeling the impact of wind stochasticity and low inertia

Due to the well-known uncertainty characteristic, wind power causes the problems in maintaining the system frequency. In the presence of wind, the frequency disturbance gets worse both in density and magnitude. As required by power system standards, the frequency deviation must remain in the safe limits. To ensure the frequency security, several methods have been proposed. In [15], [16], the reserve requirement is mandatory for the wind turbine to support frequency regulation. The wind generators have to operate below their available output power to ensure that they have ability to provide reserve for frequency regulation. The reserve requirement is implemented in wind generators by Delta control. The idea behind this control is to keep a certain power reserve to be able to respond and alter production quickly both with positive and negative power ramps. As a result, the total available of wind power might not be integrated completely into the system. Considering the reserve requirement, the reliability of wind power and of the system reduces due to the decrease of integrated wind power.

Besides the uncertainty, one of the drawbacks of wind is that wind turbines have very low inertia compared to that of conventional generators. This property of wind also introduces negative effects on the frequency regulation when wind generators replace conventional generators - larger frequency deviation and longer restoration time [17]. These

negative effects become more serious if the penetration of wind power increases [11]–[13]. Due to the negative effect of wind on system frequency, the amount of wind allowed to integrate into system is limited to ensure the system stability. The method to estimate the penetration limit of wind power has been presented in previous works based on the stability power quality criteria: system minimum reserve requirement, the network congestions, voltage stability, system capacity, frequency stability, thermal violations [23], [24], transient stability limit and frequency security constraint [25], [26], wind-thermal coordination scheduling [27]. In this paper, the fast approximation of penetration limit based on the sensitivity analysis of maximum frequency deviation is utilized [26].

To estimate the penetration limit of wind power based on frequency security, it is necessary to understand the mathematical model of the system frequency. Fig. 1 is the model of the load frequency control (LFC) for the multi-machine system proposed in [28] based on the sensitivity of the frequency deviation to the governor parameters for the low-order LFC model [29] using linear curve-fitting. The sensitivity of the maximum frequency deviation to governor parameters in [28] is shown in Table I.

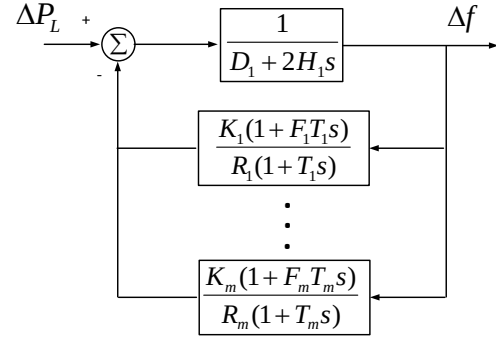


Fig. 1. Multi-machine LFC model [28].

TABLE I
SENSITIVITY OF FREQUENCY NADIR TO GOVERNOR PARAMETERS

Parameters	K	T_R	H	F_H	D	R
Min	0.8	4	3	0.1	0	0.03
Max	1.2	11	9	0.35	2	0.08
Sensitivity	0.49	-0.01	0.03	1.35	0.05	-9.14

From the sensitivity results, it is assumed in [28] that the governor time constants for the system governors are identical without losing sufficient accuracy.

Assuming that load disturbance is a step function, the frequency deviation can be shown in following equation [28]:

$$\Delta f = \frac{\frac{\Delta P_L}{s}}{D + 2Hs + \sum_{i=1}^m \frac{K_i(1 + F_iT_{Ri}s)}{R_i(1 + T_{Ri}s)}} \quad (2)$$

Taking the inverse Laplace transformation, the time-domain of

frequency deviation can be given as:

$$\Delta f = \frac{\Delta P_L}{2HT_R\omega_n^2} \left(1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \cos(\omega_n \sqrt{1-\zeta^2} t - \phi)\right) + \frac{\Delta P_L}{2H\omega_n \sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_n \sqrt{1-\zeta^2} t) \quad (3)$$

where

$$\phi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \quad (4)$$

$$\omega_n = \sqrt{\frac{1}{2HT_R}}(D + R_T) \quad (5)$$

$$\zeta = \frac{1}{2} \frac{2H + T_R(D + F_T)}{\sqrt{2HT_R(D + R_T)}} \quad (6)$$

$$F_T = \sum_{i=1}^m \frac{K_i F_i}{R_i} \quad (7)$$

$$R_T = \sum_{i=1}^m \frac{K_i}{R_i} \quad (8)$$

At the maximum frequency deviation, the derivative of frequency deviation equals zero. Hence, the time of the maximum frequency deviation and the maximum frequency deviation can be derived as [28]:

$$t_{max} = \frac{1}{\omega_n \sqrt{1-\zeta^2}} \tan^{-1}\left(\frac{\omega_n \sqrt{1-\zeta^2}}{\zeta\omega_n - 1/T_R}\right) \quad (9)$$

$$\Delta f_{max} = \frac{\Delta P}{R_T + D} \left(1 + e^{-\zeta\omega_n t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (10)$$

Assuming that the reduction in the system inertia when wind power replaces the conventional generators is n_{conv} , the inertia that wind contributes to the system is n_w , the new values of system inertia and equivalent regulation constant can be expressed by:

$$H_{new} = H_{old}(1 - n_{conv} + n_w) = nH_{old} \quad (11)$$

$$R_{new} = R_{old}/(1 - n_{conv} + n_w) = R_{old}/n \quad (12)$$

Applying the new values of H and R to equation (10), the new value of the maximum frequency deviation in the presence of wind power is given as:

$$\Delta f_{max} = \frac{\Delta P}{nR_T + D} \left(1 + e^{-\zeta_{new}\omega_{n,new}t_{max}^{new}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (13)$$

where

$$F_{Tnew} = \sum_{i=1}^m n \frac{K_i F_i}{R_i} = nF_T \quad (14)$$

$$R_{Tnew} = \sum_{i=1}^m n \frac{K_i}{R_i} = nR_T \quad (15)$$

$$\omega_{n,new} = \sqrt{\frac{1}{2nHT_R}}(D + nR_T) \quad (16)$$

$$\zeta_{new} = \frac{1}{2} \frac{2nH + T_R(D + nF_T)}{\sqrt{2nHT_R(D + nR_T)}} \quad (17)$$

To ensure system security, the maximum frequency deviation should not pass the safe limit:

$$\Delta f_{max} \leq \Delta f_s \quad (18)$$

As the value of D is often much smaller than R_T and F_T , the values of $\omega_{n,new}$ and ζ_{new} do not have notable change when changing D . Also, the sensitivity of maximum frequency deviation to D (0.05) is much less than that to R (-9.14) and F_H (1.35). Moreover, the change in load damping does not have a remarkable impact on the exponential term. Therefore, it is reasonable to approximate the values of $\omega_{n,new}$ and ζ_{new} and the limit n_{max} as follows:

$$\omega_{n,new} = \sqrt{\frac{1}{2nHT_R}}(nR_T) = \sqrt{\frac{R_T}{2HT_R}} \quad (19)$$

$$\zeta_{new} = \frac{1}{2} \frac{2nH + nT_R F_T}{\sqrt{2nHT_R nR_T}} = \frac{1}{2} \frac{2H + T_R F_T}{\sqrt{2HT_R R_T}} \quad (20)$$

$$n_{max} = \frac{\Delta P_L}{\Delta f_s R_T} \left(1 + e^{-\zeta\omega_n t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (21)$$

Based on the limit of inertia reduction, the maximum amount of wind integrated into the system is defined.

In many previous works, while evaluating the reliability of power system in the presence of wind, all of the available wind output is considered in the reliability model. However, considering the two mentioned problems which affect the amount of integrated wind power, the traditional reliability model of the system with wind power must be re-evaluated. The real amount of wind power deployed in the system is lower than the available wind output, which means the reliability of the system is negatively affected. The proposed idea will be implemented in IEEE RTS system to verify its effectiveness.

III. RELIABILITY ASSESSMENT USING MONTE CARLO METHOD

Monte Carlo is often used as an alternative way to analytical methods [30]. In general, Monte Carlo can be employed to simulate the system that has a random behavior. In system reliability assessment, Monte Carlo simulation is utilized to see how random failures of components lead to the failure of system. In this method, the system is divided into elements, whose behavior could be decided either deterministically or by probability distributions. All elements are then combined to evaluate the system reliability. Based on the mathematical model, the method performs sampling and get results from multiplied times of sampling until the result converges.

In this paper, the system generation model is constructed using sequential Monte Carlo - State duration sampling method. The first step is to generate chronological up-down-up history for each generating units using fixed time interval [31]. By generating a uniformly distributed random number and using inverse transform method, the passage time or the time in

which equipment resides in an up or a down state is calculated as follows:

$$t = \frac{-1}{\lambda} \ln(U) \quad (22)$$

where λ is the failure rate of the equipment at the up state and repair rate of the equipment at the down state. U is a uniformly distributed random number in the interval (0, 1). The time to failure and the time to repair are given as follows:

$$TTF = MTTF \times \ln(U) \quad (23)$$

$$TTR = MTTR \times \ln(U) \quad (24)$$

The reliability indices are calculated from the system power margin (system power margin = generation – load). When the margin is negative, the load power is more than the generation. From the duration of negative margin, The Loss of Load Duration (LLDi) in hour for year i can be obtained [3]. From the amount of the negative margin and for the duration of that negative power, the Energy Not Supplied (ENS i) in MWh for year i [3] is inferred. From counting the number of time the margin moves from a positive value to a negative value, the Loss of Load Occurrence (LLO i) for year i is defined [31]. The reliability indices for N sampled years can be estimated as follows:

Loss Of Load Expectation (LOLE), hr/yr:

$$LOLE = \frac{\sum_{i=1}^N (LLDi)}{N} \quad (25)$$

Loss Of Energy Expectation (LOEE), MWh/yr:

$$LOEE = \frac{\sum_{i=1}^N (ENS_i)}{N} \quad (26)$$

Loss Of Load Frequency (LOLF), occ/yr:

$$LOLF = \frac{\sum_{i=1}^N (LLO_i)}{N} \quad (27)$$

The algorithm of sequential Monte Carlo-State duration sampling method is shown in Fig. 2.

IV. SIMULATION AND RESULTS

The proposed approach is tested on IEEE-RTS system in the presence of wind. The reliability of the system is evaluated for the cases of considering and not considering the impacts of wind stochasticity and low inertia. In this study, 230 identical wind turbines with 5 MW rated power each are connected to the system and replace the three biggest conventional generators. The wind data is extracted from [32] which is provided by National Renewable Energy Laboratory (NREL). Fig. 3 shows wind fluctuation over the period of one year. Available data are collected over ten minutes periods. However, the data is clustered into one hour periods. The cut-in, rated and cut-out speed of wind turbine are 4, 12, and 25 m/s, respectively. Based on the wind speed provided, the wind power output is calculated. Three case studies will be investigated.

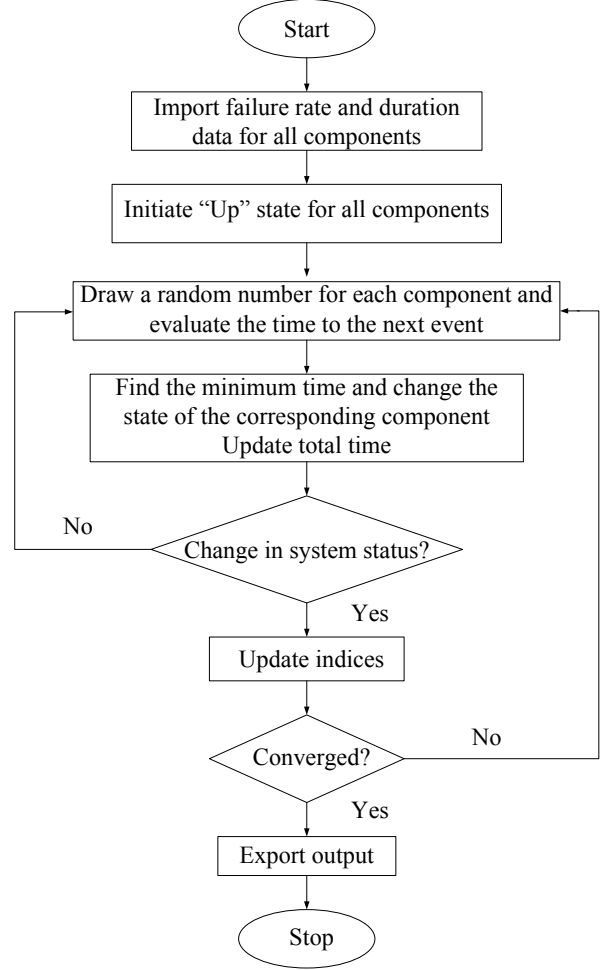


Fig. 2. Algorithm of Monte Carlo simulation method.

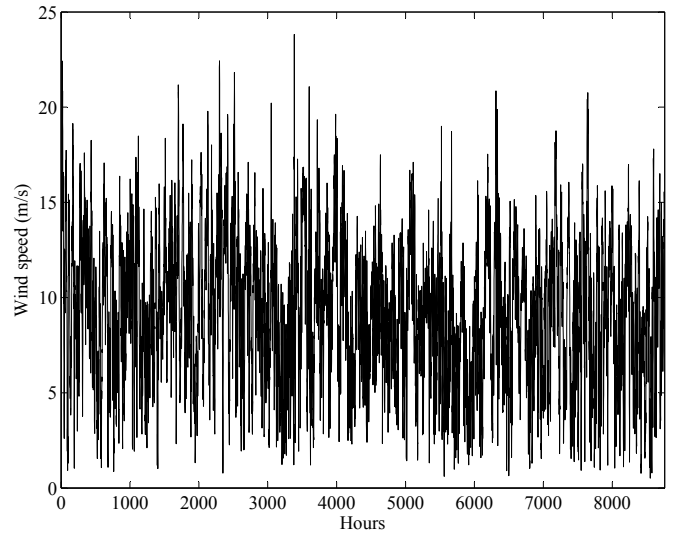


Fig. 3. Wind speed values over a year.

Case 1: The reliability indices of the system are examined when the total available wind power is integrated into the system.

Case 2: Considering the reserve requirement, the wind generators have to operate at the lower level of its available power output. Assuming that the spinning reserve requirement of wind generation is 20% of wind available output, the wind power that integrates into system reduces. As a result, the reliability of system gets worse. The comparison of available wind power and real wind power that integrates into system for the 200 hours can be seen in Fig. 4.

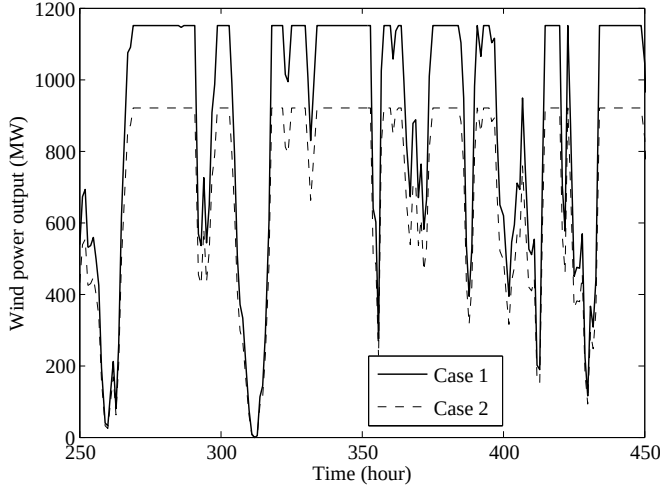


Fig. 4. Available wind output and integrated wind output considering the spinning reserve requirement.

Case 3: Considering the impact of stochasticity and low inertia of wind, the integrated wind power must be limited to ensure the stability of the system. This is implemented by the limit of reduction of inertia as presented in the previous section. The dynamic data of the system is chosen within appropriate the ranges which are shown in Table I [28] and based on the capacity of each generators [33]. The system load damping is assumed a value of 2. Load disturbance is simulated by a 0.5 pu step function. The inertia of a wind turbine is much less than that of a conventional generator and is chosen by 0.03.

Applying the dynamic data of conventional generator to the equation (21) and considering the safe range of frequency deviation to be $\pm 0.1\text{Hz}$ [34], the maximum reduction of inertia of the system n_{max} is 24%. As the inertia of the system is directly proportional to the output of the conventional generator, the maximum penetration limit of wind generation is 837 MW considering the small contribution of wind inertia. This condition will be combined with the spinning requirement of wind to give the real allowable integrated wind power. The comparison of available wind power and real wind power that integrates into system considering both spinning reserve requirement and frequency security condition for the 200 hours can be seen in Fig. 5. The reliability indices of IEEE-RTS system with and without considering the reserve requirement

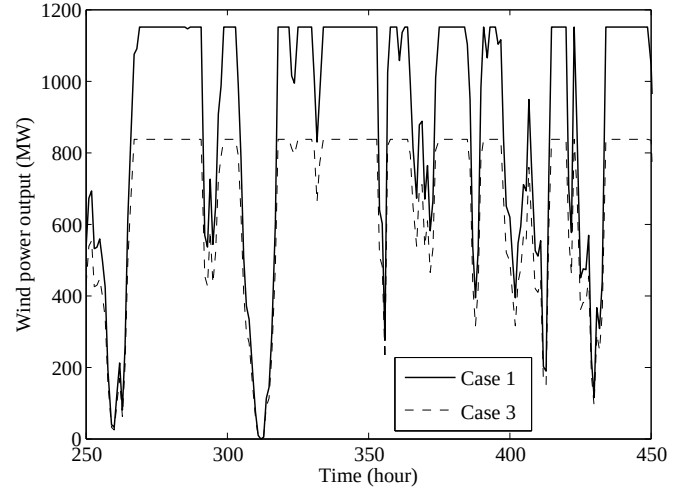


Fig. 5. Available wind output and integrated wind output considering both the spinning reserve requirement and frequency security.

and the frequency security are shown in table II. The change of LOLE, LOEE and LOLF with the number of sample years for three cases is shown from Fig. 6 to Fig. 8.

TABLE II
THE RELIABILITY INDICES OF IEEE-RTS SYSTEM FOR THREE CASES STUDY

Index	LOLE (hr/yr)	LOEE (MWh/yr)	LOLF (occ/yr)	LOLP	EDNS (MW/yr)
Case 1	497.5	89170	114.6	0.057	10.2072
Case 2	553.7	98813	121.1	0.063	11.312
Case 3	557.5	99543	121.3	0.064	11.3945

From the simulation results, it is clear that the operation conditions (spinning reserve requirement, frequency security) have negative effects on the reliability of wind power. In the presence of these conditions, all the reliability indices get worse. To enhance the reliability of the system, improving the wind forecast, the inertia of wind via advanced control strategies, application of energy storage can be helpful.

V. CONCLUSION

This paper has presented the effect of stochasticity and low inertia properties of wind power on the reliability of the system. The work has proved that the reliability of the integrated system decreases when considering the requirement of the system to ensure the system security. This has been the drawback that most of the previous work overlooked. The proposed method's validity has been investigated and supported with a mathematical analysis and simulation. The technique presented will benefit the system operator in accurate predicting the failures of the system when the renewable energy is getting a higher and higher portion in the energy system.

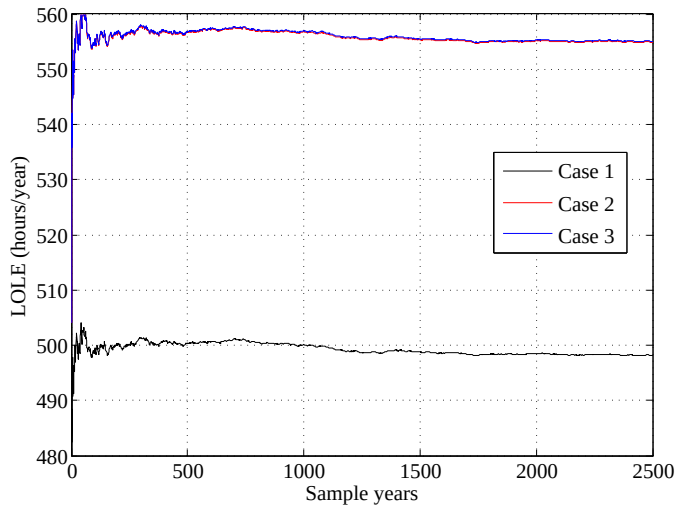


Fig. 6. LOLE versus the number of sample years.

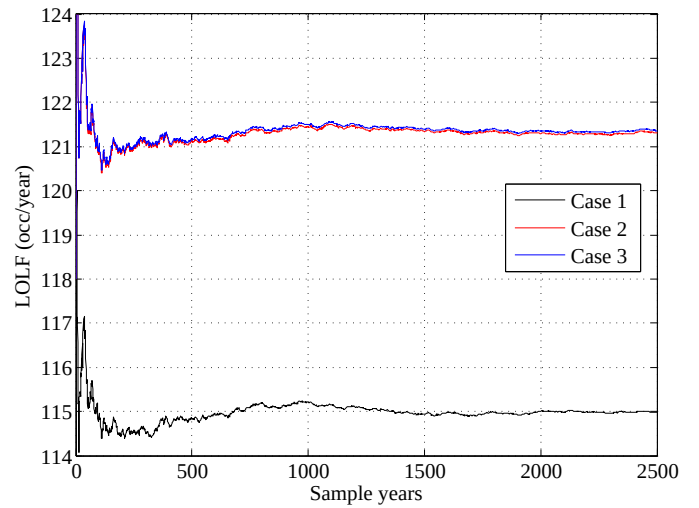


Fig. 8. LOLF versus the number of sample years.

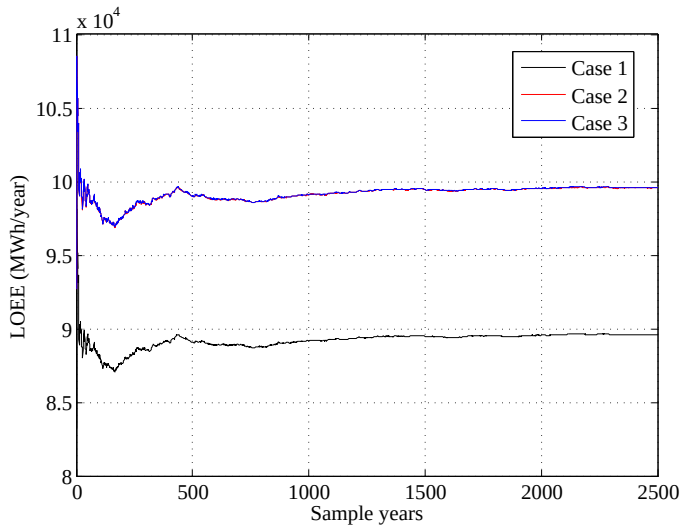


Fig. 7. LOEE versus the number of sample years.

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