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Operational reliability assessment considering independency between wind power ramps and frequency sensitive loads

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Abstract. With the increasing wind power penetration, power system frequency is more vulnerable especially when gust wind periods. Frequency control is used to restore system frequency back to the rated value. But, during frequency control processes, demand of frequency sensitive load (FSL) is different from that of frequency-insensitive load and changes with the change in system frequency. It is necessary to consider load demand combined with dynamic frequency deviation. This paper proposed a new reliability evaluation method of generation systems based on blade-element theory and frequency control method. The blade-element theory is utilized to improve the evaluation accuracy of wind power output in the presence of wind power ramp events (WPREs). The frequency control considering dynamic demand of FSL is used to mimic frequency regulation processes and establish reliability evaluation model. Case studies are presented using wind data from a wind farm in Shanxi Providence, and the results suggest that reliability problems caused by FSL can't be ignored in some cases.

1 Introduction

Operational reliability (OR) plays an important role to measure instantaneous balance between supply and demand. OR is defined in [1] as: "the reliability actually observed during operation." According to this definition, the horizon of power balance may vary from several minutes to several hours, classified into short-term periods such as frequency regulation processes and long-term periods such as load shedding or load shifting periods.

Conventional reliability considering load characteristics puts more emphasis on long-term reliability evaluation [2-6]. Therefore, many works carried out so far take long-term power system planning and reliability evaluation into consideration. A methodology has been proposed in [2] to evaluate loss of load indices with a long time horizon for composite generation and transmission systems. In [3], a tri-level reliability-constrained robust power system expansion planning framework has been proposed to model the uncertainty of electricity demand, wind power generation, and availability of units and lines. In [4], a reliability-oriented planning model has been established to design reliable topologies for meshed high-voltage direct current grids.

With the increasing wind power penetration, the short-term reliability issues caused by WPREs have been paid more and more attentions [7]. The increment in wind farms and the reduction in thermal power plants make power system more vulnerable to the WPREs. Automatic generation control (AGC) units may frequently regulate power generation to balance supply and demand. Due to the fact that power system operation modes have changed from the old "weak randomness" to the modern "strong randomness", the number and duration of frequency control may increase compared with that of conventional operation mode. Under this new operation mode, energy spill and shortage during frequency control processes can't be neglected. This conclusion has been confirmed by the published papers [8-9]. But, those works assume that FSL is same as the resistive load with fixed demand during frequency restoration processes.

Operational reliability is directly affected by the load model adopted. Peak load, average load, chronological load curve, and load duration curve are models widely used in the reliability evaluation of generation systems [10-11]. However, some kinds of load such as motors are sensitive to frequency deviation. For instance, the demand of FSL changes with the change in system frequency. Load damping coefficient (D) is an important parameter in power system to reflect the quantity of FSLs connected to the power system. In traditional way, FSL is often represented by the parameter D that is always a constant value in theoretical analysis. In fact, D is sensitive to frequency excursion and is a time-varying value. The error of D between theoretical value and practical value is always existed, leading to the energy spill or shortage

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during frequency response processes. For instance, because of wind power ramp events (e.g. wind power significant increases or decreases in a short time period, WPRE), the electrical frequency may exceed operation limits of power system. Frequency controls including primary and secondary frequency control are carried out to restore system frequency. Different errors of D result in different frequency response curves. That is, the error of D determines the area enclosed with vertical axis of frequency deviation and horizontal axis of time. This area reflects the energy flow during frequency control processes. Note that energy flow caused by the error of D could sometimes give rise to severe consequence for frequency stability. Therefore, an operational reliability evaluation method should be proposed to evaluate the impact of FSL-based energy flow on generation system reliability.

The remainder of the paper is organized as follows: in Section II proposes a dynamic wind turbine generator model taking blades' inertia into consideration for preparation of following reliability evaluation. In Section III establishes low-order frequency control model. In Section IV, the frequency response function is derived by using inverse Laplace transformation with considering time-varying parameter D, so as to determining the energy flow during frequency control processes. The detailed reliability evaluation methods and corresponding reliability indices are illustrated in Section VI and Section V respectively. Results are presented and discussed in Section VII. Finally, conclusions are drawn are provided in Section VIII.

2 Modeling dynamic wind turbine generator

Unstable wind speeds, especially a sudden change in wind speed, are more prone to produce WPREs, leading to frequency excursion and corresponding reliability problems. In response to wind gust, how much electric power generated by a wind turbine generator (WTG) is a question needed to be answered. As a traditional way to evaluate wind power, power curve should be determined. Power curve is a plot of output power against wind speed and often represented by different functions, such as quadratic function [12] and cubic function [13]. The limitations of conventional methods are shown in bellow.

- Power curve of conventional models are based on maximum power point tracing (MPPT) technology and describes maximum power output. Fig.1 shows that the relationships between wind speed and blades' rotation speed make the differences in WTG power generation (see the red dashed line). Maximum power generation is only possible when a good matching performance is achieved. For instance, if wind speed is v=v_1 and the corresponding rotation speed is n=n_1. Those well-matched operation states usually appear when wind speed is relative stable. Therefore, the conventional models are defined as steady-state model.
- Power curve is a fitting curve obtained from real-time wind power data of individual WTG and properly reveals the statistic-characteristics of wind power during a long time. But, some WTG operation states can't be reflected by a probabilistic model. For example, as shown in Fig.1, there is a rapid increase in wind speed from v_4 to v_1. But, blades' rotation speed can't immediately increase from n_1 to n_4 due to the blades inertia. Therefore, WTG goes beyond operation modes described by conventional methods because wind speed. Therefore, traditional methods are hard to accurately evaluate WTG output in the presence of a sudden gust of wind.

Therefore, a novel WTG output model based on blade element-momentum theory (BEMT) [14] should be proposed to improve the evaluation accuracy. The proposed model, defined as full-state model by authors, includes steady-state model and transient-state model. The transient-state part takes blades' inertia into consideration and is used to evaluate the power generation when wind speed is unstable.

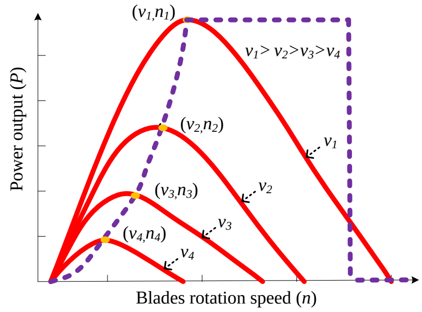

Fig. 1. Power curve of wind turbine generator

The hourly output of a WTG considering the time-varying blade rotation speed (n) can be obtained from the wind speed and correction factor (CF) by applying the following equation:

$$P(V,n)=\begin{cases} 0\times CF & 0\le V\le V_{ci} \\ \left(A+B\times V+CV^2\right)\times P_r\times CF & V_{ci}\le V\le V_r \\ P_r\times CF & V_r\le V\le V_{co} \end{cases} \tag{1}$$

where P_r, V_{ci}, V_r. and V_{co} are the rated power, the cut-in wind speed. the rated wind speed and the cut-out wind speed of the WTG respectively.

3 Modeling low-order frequency control

In order to contain dynamic behavior of FSL into reliability evaluation process, one of the more prominent problems is to rapidly transform transfer function from s-domain into time domain. In order to reduce computational burden, reduced order model may be of vital importance. The order reduction techniques derived from paper [15] have been used to establish a low-order frequency control model.

3.1 Existing frequency control model

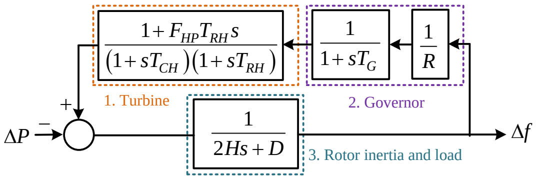

Fig. 2. Traditional SFR Model without considering AGC

The full frequency control model shown in Fig. 2 shows that the unbalanced active power (*ΔP*) leads to frequency deviation (*Δf*). During frequency regulation process, the most significant time constant in this system is the reheater time constant, identified as T_{RH} in Fig. 2. This constant is usually in the range of about 6 to 12 seconds and tends to dominate the response of the largest fraction of turbine power output. The second dominant time constant in the system is the inertia constant, called H in Fig. 2. This constant is on the order of 3 to 6 seconds for a typical large unit and is always multiplied by two. Therefore, all the smaller time constants as insignificant compared to T_{RH} and H need to be ignored. The stable Δf in Fig. 2 is equal to $\Delta P/(1/R+D)$. In order to get the same stable frequency deviation, the speed regulation coefficient $1/R$ and load-damping coefficient D should be retained in simplified model. Given the above, the simplified low-order frequency control model is shown in Fig. 3.

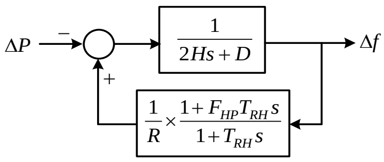

Fig. 3. A low-order frequency control model

The frequency control model shown in Fig. 3 can be regarded as primary frequency control due to the ever-present frequency error. Secondary frequency control which is performed by the automatic generation control (AGC) adjusts load reference set points of AGC units and adjusting their outputs to restore system frequency. In order to simulate the frequency restoration processes, proportional-integral (PI) control has been added in Fig. 4 where the proportional coefficient K_I reflects the power regulation speed of AGC units.

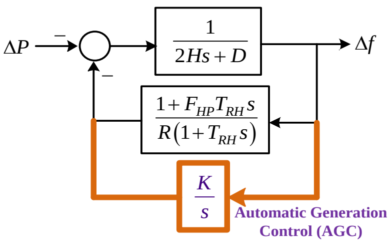

Fig. 4. A low-order frequency control model with considering AGC.

4 Modeling frequency response processes

From the above description, parameter D in Figures 2 to 4 is a constant value. But, in system real operation, D changes with the change in system frequency. How to consider the impact of error of D on dynamic response processes of frequency control is a problem needed to be answered. This paper combines Laplace transform with Total Differential Equations to determine frequency response function [16].

4.1 Frequency control without considering dynamic FSL

Consider the LFC block diagram of a simple single machine system with AGC in Fig. 4. The closed-loop transfer function relating the load change (*ΔP*) to the frequency deviation (*Δf*) is as follows:

$$G(s)=\frac{\Delta f(s)}{\Delta P(s)}=\frac{1}{2Hs+D+\left[\dfrac{K}{s}+\dfrac{1+F_{HP}T_{RN}s}{R(1+T_{RH}s)}\right]} \tag{2}$$

Therefore:

$$\Delta f(s)=G(s)\times\Delta P(s) \tag{3}$$

The frequency deviation related with external disturbance is considered based on total differential method which can illustrate the change of frequency when each of the variables receives an increment. The differential equation of $\Delta f(s)$ is as follows:

$$d\Delta f(s)=\frac{\partial\Delta f(s)}{\partial\Delta P(s)}d\Delta P(s) \tag{4}$$

Furthermore, taking partial derivative for of equation (3) we have:

$$\frac{\partial\Delta f(s)}{\partial\Delta P(s)}=G(s)=\frac{\Delta f(s)}{\Delta P(s)} \tag{5}$$

In order to have its time domain description, Laplace inverse transformation is applied to (4). Thus, we have:

$$d\Delta f(t)=L^{-1}\left[d\Delta f(s)\right]=L^{-1}\left[G(s)d\Delta P(s)\right] \tag{6}$$

Integration of (6) gives:

$$\begin{aligned}\Delta f(t)&=\int L^{-1}\left[G(s)d\Delta P(s)\right]\\&=L^{-1}\left[G(s)\times\int d\Delta P(s)\right]=L^{-1}\left[G(s)\times\Delta P(s)\right]\end{aligned} \tag{7}$$

Steady component is equal to zero because PI control restores system frequency back to the rated value. Transient component is an attenuation function which includes primary frequency control and secondary frequency control.

4.2 Frequency control with considering dynamic FSL

Another interesting point should be mentioned is about the effect of the time-varying D on the frequency control. In equation (4), the effect of the load-damping coefficient in this SFR model is ignored. Frequency variation ΔF should be a function of ΔP and D rather than ΔP only. Thus, it is interesting to investigate the impact of time-varying D. With the assumption that ΔP and D are mutually independent, equation (4) should be modified to include D as follows:

$$d\Delta f(s)=\frac{\partial\Delta f(s)}{\partial\Delta P(s)}d\Delta P(s)+\frac{\partial\Delta f(s)}{\partial\Delta D}d\Delta D \tag{8}$$

Furthermore, taking partial derivative for of equation either

$$\begin{aligned}\frac{\partial\Delta f(s)}{\partial\Delta D}&=\frac{\Delta P(s)}{\left[2Hs+D+\frac{K}{s}+\frac{1+F_{HP}T_{RH}s}{R(1+T_{RH}s)}\right]^2}\\&=\left[\frac{\Delta f(s)}{\Delta P(s)}\right]^2\Delta P(s)\end{aligned} \tag{9}$$

Combining (5) (9) with (8), we have

$$d\Delta f(s)=\frac{\partial\Delta f(s)}{\partial\Delta P(s)}d\Delta P(s)+\left[\frac{\Delta f(s)}{\Delta P(s)}\right]^2\Delta P(s)d\Delta D \tag{10}$$

In order to have its time domain description, Laplace inverse transformation is applied to (10). Thus, we have:

$$\begin{aligned}d\Delta f(t)&=L^{-1}\left[d\Delta f(s)\right]\\&=L^{-1}\left[\frac{\Delta f(s)}{\Delta P(s)}d\Delta P(s)\right]+L^{-1}\left\{\left[\frac{\Delta f(s)}{\Delta P(s)}\right]^2\Delta P(s)d\Delta D\right\}\end{aligned} \tag{11}$$

Integration of (11) gives:

$$\begin{aligned}\Delta f(t)&=\int L^{-1}\left[d\Delta f(s)\right]\\&=\int L^{-1}\left[\frac{\Delta f(s)}{\Delta P(s)}d\Delta P(s)\right]+\int L^{-1}\left\{\left[\frac{\Delta f(s)}{\Delta P(s)}\right]^2\Delta P(s)d\Delta D\right\}\\&=L^{-1}\left[G(s)\times\Delta P(s)\right]+L^{-1}\left\{\frac{\Delta D\times\left[\Delta f(s)\right]^2}{\Delta P(s)}\right\}\end{aligned} \tag{12}$$

The comparison of (7) and (12) shows that steady components with or without considering the impacts of FSL are the same due to application of an errorless control method—PI control, and transient components exist differences because the second one takes into account FSLs. The derivation processes prove that the differences in frequency curves lead to the errors in energy flow of frequency regulation processes and then pose a barrier to the accuracy of operational reliability.

5 Reliability indices

The conventional frequency control assumes the power consumptions of FSLs increase linearly with frequency deviation and model the aggregate power consumption of these loads by $P+D\times\Delta f$ with $D\geq 0$, where P is its nominal value. But in practice, the time-varying D is approximately equal to $D+\Delta D(t)$, where D is the average value and $\Delta D(t)$ is a real-time fluctuant component that is usually ignored in existing frequency control methods. After taking $\Delta D(t)$ into consideration, the modified frequency response functions have been derived in above section. Based on those functions, reliability indices are proposed to analyze impact of FSL on energy shortage or waste of frequency control processes.

The expected energy shortage (EES) (MWh/Month) is analyzed when $\Delta D(t)\leq 0$. The power regulation ability of load $D+\Delta D(t)$ is less than D. If active power regulation ability is equivalently replaced by a D-based frequency control model, actual regulation ability is over-estimated. There is a generation shortage resulted from $\Delta D(t)$. Such generation shortage should have been compensated to stabilize system frequency. Due to the everlasting error $\Delta D(t)$ in the processes of restoring frequency, energy shortage is impossible to eliminate and therefore would be viewed as a complement for traditional adequacy indices—expected energy not supplied (EENS) [17]. In this paper, the reliability impact assessments of energy shortage are implemented based on frequency restoration processes. According to a multi-stage frequency control, EES is divided into two parts including ES of primary control process and ES of secondary control process. Although such energy shortage is not caused by load curtailment, it does affect system dynamic regulation and should be considered in operational reliability evaluation that puts more emphases on reliability problems related to real-time operation of power system. The expected energy waste (EES) (MWh/Month) is defined as

$$EES=\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}p_{ij}\times\left(ES_{ij,1}+ES_{ij,2}\right) \tag{13}$$

where N_j is the number of the states to be considered, $ES_{ij,1}$ (MWh) and $ES_{ij,2}$ (MWh) are the energy shortage for wind speed i and state j caused by the primary control and the secondary control respectively. The p_{ij} is system state probability for wind speed i and state j.

The expected energy waste (EEW) (MWh/Month) is analyzed when $\Delta D(t)>0$. The frequency regulation ability of load $D+\Delta D(t)$ is less than D. That is, the frequency regulation ability of power system has been under-estimated, and then loads get the additional power supply that is usually neglected in conventional reliability analysis. Such power supply is defined as energy waste because it should have been reduced to stabilize system frequency. Due to the existing error $\Delta D(t)$ caused by dynamic demand of FSLs, energy waste is impossible to eliminate and therefore would be viewed as a complement for traditional adequacy indices—expected energy not used (EENU) [8]. In this paper, the impact assessments of energy waste are implemented based on real time frequency response. According to different frequency control processes, EEW is divided into two parts including EW of primary control process and EW of secondary control process. Although such energy waste is not caused by wind curtailment concerned by conventional reliability index EENU, it does affect system dynamic regulation and should be considered in operational reliability evaluation. The expected energy waste (EEW) (MWh/Month) is defined as

$$EEW = \sum_{i=1}^{N_i}\sum_{j=1}^{N_j} p_{ij} \times \left(EW_{ij,1} + EW_{ij,2}\right) \tag{14}$$

where $EW_{ij,1}$ (MWh) and $EW_{ij,2}$ (MWh) and are energy waste for wind speed i and state j in the primary and secondary control respectively.

6 Formulation of reliability indices

A typical frequency restoration curve associated with a WPRE is shown in Fig. 5. The WPRE usually lasts from seconds to several hours after the event occurs at t_o. Once the WPRE is occurred, active power fluctuation caused by WPRE may lead to frequency deregulation. As the power system frequency enters the degradation phase from t_o to t_2, frequency control should be taken by the aid of observation system so that restore system frequency to pre-event level of performance. This paper puts more emphasis on the generally neglected energy shortage or spill caused by FSL during frequency regulation processes. The reliability indices formulation is implemented based on the following case.

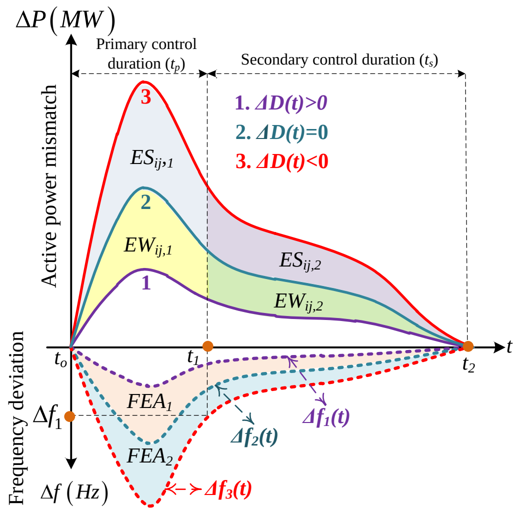

Fig. 5. Frequency control process and the associated ES and EW.

Fig. 5 shows the frequency control processes represented by full lines and active power regulation processes represented by dashed lines. The real time frequency curves and power curves under same control method are represented by the same color. If there is no errors between theoretical value and the actual value of the load damping coefficient, $\Delta D(t)$=0, the dynamic real-time frequency curve is marked as $\Delta f_2(t)$. After the $\Delta D(t)$ is taken into consideration, the dynamic frequency curve is revised and marked as $\Delta f_1(t)$ or $\Delta f_3(t)$.

If $\Delta D(t)$>0, compare with the D-based frequency control system, power system experiences a little fluctuation in frequency due to the increase of load damping coefficient from D to $D+\Delta D(t)$. After taking positive $\Delta D(t)$ into consideration, the revised frequency response curve is marked as $\Delta f_1(t)$. The frequency error area one (FEA1) caused by positive $\Delta D(t)$ is enclosed by $\Delta f_1(t)$ and $\Delta f_2(t)$, which leads to corresponding energy wastes enclosed by line 1 and line 2. Those energy wastes, including $EW_{ij,1}$ and $EW_{ij,2}$, depend on real-time unbalanced power and frequency control duration. Unbalanced power is reduced during frequency control processes. Frequency control duration relies more on parameter selections of PI control. Automatic control theory [16] shows the changes in parameter D only change the curve profile of frequency deviation rather than frequency control duration. Therefore, durations of a particular frequency control stage such as primary frequency control or secondary frequency control are almost the same for different numeric values of $D+\Delta D(t)$. Therefore, the reliability indices associated with energy waste can be calculated as:

$$\begin{cases} EW_1 = \int_{t_0}^{t_1}\left[\Delta f_1(t) - \Delta f_2(t)\right] \times R_S dt \\ EW_2 = \int_{t_1}^{t_2}\left[\Delta f_1(t) - \Delta f_2(t)\right] \times R_S dt \end{cases} \tag{15}$$

where t_1 is primary frequency control durations. t_2 is the total duration of frequency control. The t_1 and t_2 can be calculated by iteration processes when frequency deviation reaches to $\Delta f_1=[\Delta P/(R+D)]$ and Δf_2=0 respectively. R_s is the frequency regulation ability of power system (MW/Hz).

If $\Delta D(t)$<0, frequency regulation ability of power system is less than that of D-based frequency control model shown in Fig.4. By comparison with simulation system with constant D, power system with a small value of load damping coefficient $(D+\Delta D(t))$ experiences a strong fluctuation in frequency. Therefore, the frequency response curve considering negative $\Delta D(t)$ is marked as $\Delta f_3(t)$. Between $\Delta f_2(t)$ and $\Delta f_3(t)$, there is a frequency error area two (FEA2) caused by negative $\Delta D(t)$, which leads to corresponding energy shortages enclosed by line 2 and line 3. Those energy shortages for different control processes, including $ES_{ij,1}$ and $ES_{ij,2}$, is the integral of real-time power shortage and frequency control duration. Therefore, the reliability indices associated with energy shortage can be calculated as:

$$\begin{cases} ES_1 = \int_{t_0}^{t_1}\left[\Delta f_2(t) - \Delta f_3(t)\right] \times R_s dt \\ ES_2 = \int_{t_1}^{t_2}\left[\Delta f_2(t) - \Delta f_3(t)\right] \times R_s dt \end{cases} \tag{16}$$

7 Application to a practical system

The thermal power plants and load power in Shanxi province of China are simulated to illustrate the proposed models and indices. The total installed capacity of CGs is 19140 MW and the monthly peak load is 18750 MW. The parameters of the CGs are shown in Table 1. The unit commitment order under different load is from large to small units. All the committed CGs proportionally share the total load and spinning reserve based on frequency regulation ability. The *D*, T_{RH} and F_{HP} for the equivalent control units are 10, 7.0 s and 0.3 respectively [18]. The system states with the probability being less than 10^{-7} are truncated during the simulation. The values of parameter *R* is derived from engineers working in coal-fired Power Plant in Shanxi province.

Table 1. Generator data of Shanxi province.

Unit Group	R (MW/Hz)	U
U50 (MW)×10	25	5.0×10^{-4}
U100 (MW)×3	67	8.3×10^{-4}
U135 (MW)×10	89	1.0×10^{-3}
U330 (MW)×23	200	8.7×10^{-4}
U500 (MW)×2	240	8.7×10^{-4}
U600 (MW)×14	467	9.1×10^{-4}

7.1 Reliability indices without and with considering FSL load

To make clear the importance of energy shortage or spill caused by FSL, we should analyze the proportion of energy shortage or spill caused by FSL in the total power mismatch of frequency control processes. The total power mismatch with $\Delta D(t)$=0 is divided into two parts including expected indirect energy not supplied (EIENS) and expected unnecessary energy consumption (EUEC). The detailed information about those two reliability indices can be found in reference [9].

The conventional units used in the case studies are shown in Table 2. The analyses were conducted assuming that the parameter *D* is constant. The frequency-related reliability indices with $\Delta D(t)$=0 are simulated using proposed reliability technique. The monthly EEUC and EIENS of the system based on the proposed model of wind turbine generator are 6.1482 MWh and 12.1696 MWh respectively.

Table 2. The total Energy shortage or spill during frequency control processes.

Reliability indices	Without considering FSL
EIENS (MWh)	6.1482
EUEC (MWh)	12.1696

Table 3. The Energy shortage or waste caused by FSL during frequency control duration

Reliability indices	With considering FSL	Per. (%)
EES_1 (MWh)	0.2559	19.8204% $= 1.2186/6.1482$
EES_2 (MWh)	0.9627	
EES (MWh)	0.2559+0.9627=1.2186	
EEW_1 (MWh)	0.5815	23.4699% $= 2.8562/12.1696$
EEW_2 (MWh)	2.2746	
EEW (MWh)	0.5815+2.2746=2.8562	

Similar analyses are conducted assuming that the parameter *D* is a time-varying value. The value of ΔD is set as ±6. For each power system state *j*, the value of ΔD is determined by randomly selecting one from the above two values. The primary control based EES_1 and EEW_1 of the system are 0.2559 MWh and 0.9627 MWh respectively. The secondary control based EES_2 and EEW_2 of the system are 0.5815 MWh and 2.2746 MWh respectively. It is important to note that the energy shortage or spill caused by FSL can't be ignored when wind farm frequently experiences large wind speed fluctuations. The proportion of EES to EIENS is 19.8204%., and energy waste caused by FSL accounts for 23.4699% of total waste. The percentage will increase as the number of wind speed fluctuations goes up, and should be in line with the wind power penetration and weather conditions.

8 Conclusion

This paper has proposed a reliability evaluation method to evaluate the energy shortage or spill caused by WPRE and FSL. Combined Laplace transform with Total Differential Equations, frequency response considering dynamic demand of FSL is introduced to establish reliability evaluation model and corresponding reliability indices. Reliability evaluation results are analyzed in case studies, from which the following conclusions can be drawn: 1) the reliability problems caused by FSL can't be ignored for a wind farm suffered from gust wind periods; 2) if the variation of wind speed and corresponding deviation of blades' rotation speed go beyond a certain limits, energy shortage or spill caused by FSL should be considered in operational reliability evaluation. The reliability evaluation method proposed in this paper can provide more accurate reliability indices for power system with significant wind power penetration. In the further, considerable efforts will be devoted to develop the aging failure model considering the functional age of WTGs.

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