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A New Approach on Development of Power System Operational Flexibility Index by Combination of Generation Unit Flexibility Indices

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ABSTRACT: Power system flexibility is the ability of power system to cope with the uncertainty and variability of generation and load sides. This ability should be quantified and measured by a suitable index to show the level of system flexibility in different situations. Flexibility area index, proposed by the authors, is a suitable metric for power system flexibility evaluation, especially in the presence of renewable sources as large scale wind and solar farms. Similar to other system flexibility indices, this index is defined first for one generation unit and then, extended to the power system by combination of the unit indices. In this way, an accurate and meaningful combination routine should be established to reflect the effect of each unit flexibility index correctly in the combined system flexibility index.

This paper proposes a suitable and justified method to combine the unit flexibility indices, achieving the system flexibility index. The performance of the proposed index is verified by the wind/load curtailment in economic load dispatch incorporated wind power. Achieving this purpose, the mentioned index is decomposed into two components, one for ramp up and maximum generation system capabilities (upper component) and another for ramp down and minimum generation system capabilities (lower component), each related to the load or wind curtailment respectively which is another contribution of this paper. Finally, by establishment of a correlation between upper/lower component and load/wind curtailment, a suitable validity evaluation for the proposed system flexibility index is performed, which is another contribution of this paper.

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1- INTRODUCTION

The rapid growth of renewable energy sources in power systems leads to increasing the uncertainty and variability of power system generation. Power system flexibility is the ability of the power system to cope with uncertainty and variability, in generation and demand sides in different time horizons. A comprehensive concept of the power system flexibility can be found in [1] as:

The term flexibility describes the ability of a power system to cope with variability and uncertainty in generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons.

As the term "reliability at a reasonable cost" defines, we need to quantify the power system flexibility and, find its economic value. Therefore, the economic trade-off should be done between flexibility and power system costs (or operation cost), to find the reasonable cost. It also leads to the suitable flexibility level of each power system and operation point.

Operational flexibility plays a major role in the power system operation. Operational flexibility is the technical ability of a power system unit to modulate electrical power feed-into the grid and/or power out-feed the grid over time. This means the technical ability of a grid operator to modulate the power in-flow/outflow on a global scale (i.e. to achieve power balance), and within a grid topology (i.e. to control the power flows by the modulation of the power injections), and outtakes at specific grid nodes [2].

For a very long time, the only load demand was the main source of uncertainty and variability, and the main solution to overcome this challenge was the generation reserve of both static and dynamic reserves. By the appearance of the other sources of uncertainty and variability in the power system, mainly renewable energy sources, power system flexibility is now a serious challenge in the power system and research in different fields, such as power system flexibility evaluation and improvement, power system flexibility quantification and indices, power system flexibility modeling, etc. On the other hand, energy storage systems are one of the main tools of power system flexibility improvement, and their rapid technology growth and cost reduction are considerable.

The main focus of this study is to introduce the power system flexibility index, and to verify it in the presence of wind power as the main source of uncertainty and variability in the generation system. In this way, by using the Flexibility Area Index (FAI) presented in [3], a new method for the combination of flexibility indices of the generation units is

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developed to achieve the system flexibility index. The lack of power system flexibility mainly leads to load curtailment or renewable curtailment which guides to verify the proposed index performance. It can also open a new approach for economic trade-off [4]. It is expected reduction in wind/load curtailment by improvement of system flexibility index and vice versa. This correlation is surveyed in this paper as a contribution and the proposed flexibility index is validated by this correlation. On the other hand, by suitable decomposition of system flexibility index into two components, each of them is correlated to wind or load curtailment correspondingly which is another contribution. The main contributions of this paper are as bellow:

a) Introducing a justified method of the combination generation unit flexibility indices to get system flexibility index.

b) Decomposition the system flexibility index into up/down components corresponds to the ability of the power system to overcome up/down generation/load unbalance.

c) Establish a correlation between the up component and the load curtailment, and between the down component and the wind curtailment to verify the proposed system flexibility index performance.

The next sections of this study are as follows: In the second part, a review on the power system flexibility evaluation and the main indices is performed. Part 3 illustrates the flexibility area index approach, proposed by the authors in [3], though in this study the proposed method is presented to extract the system flexibility index by flexibility area approach. This is the main contribution of this study. Part 4 describes the main formulation of Economic Load Dispatch (ELD) incorporating wind power, and part 5 describes the solution algorithm. The mathematical verification method for the system flexibility index based on Pearson correlation coefficient is presented in part 6. The validation and verification tool for the proposed flexibility index are described in this section. Part 7 includes the simulations and discussions, and conclusion is presented in part 8.

2- FLEXIBILITY EVALUATION AND INDICES

The power system flexibility evaluation is a main task to provide the bright vision of the power system ability to maintain generation/load balance against uncertainties and variabilities in the power system. The flexibility indices are the main tools for the power system flexibility evaluation. The flexibility index for each generation unit is the base index to achieve power system flexibility index. Mainly, the power system flexibility index is obtained by combining the flexibility indices of the generation units. Generally, the power system flexibility index should satisfy two main criteria as:

a) The generation unit/system flexibility index should give a bright and meaningful view of the generation flexibility and can be easily converted to economic value to be compared with other system costs and penalties.

b) A suitable and acceptable routine should be established to combine the flexibility indices of the generation units to achieve the power system flexibility index.

It is clear that the generation/load unbalance will be reduced by improving the system flexibility. On the other hand, flexibility improvement imposes additional costs, such as more reserve preparation or energy storage equipment. Thus, the flexibility index should be suitably converted to economic value in order to be combined with other system costs to yield the best system economic trade-off. A very simple and similar approach in the power system reliability field is Energy Not Supplied (ENS) index, which is a meaningful and economic criterion that can be combined easily with other power system costs. However, there is not a comprehensive and globally accepted index in the power system flexibility yet.

A valuable method for assessing the needed operational flexibility of the power systems, for example for accommodating high shares of wind power feed-in, has been proposed by Makarov and et al., in [5]. The following four metrics have been characterized:

a) Power provision capacity π (MW).

b) Power ramp-rate capacity ρ (MW/min).

c) Energy provision capacity ε (MWh) as well as

d) Ramp duration δ (min).

Since the ramp duration δ is dependent on the power ramp rate ρ, and the power capacity π as $\delta = \pi/\rho$, it is sufficient to use the power-related metrics ρ, π and ε to describe flexibility [2]. This approach is described later in this study.

A famous and very simple flexibility index is introduced for each generation unit as (1) [6]:

$$flex_i = \frac{0.5*\left(P_i^{max} - P_i^{min}\right) + 0.5*Ramp\Delta t}{P_i^{max}} \tag{1}$$

Where Ramp is the mean of Rampup and Rampdn. Then, the system total flexibility is the combination of all the unit flexibility indices as:

$$Flex = \frac{\sum_{i=1}^{n} flex_i P_i^{max}}{\sum_{i=1}^{n} P_i^{max}} \tag{2}$$

This index is very simple and suitable for flexibility evaluation in the power system planning, but it cannot be used for operation purpose. The main reason is no relation of this index to the operation point.

As illustrated before, three main components are the base of the power system flexibility index in ELD analysis as ramp rate (ρ), power capacity (π) and energy capacity (ε), but in Unit Commitment (UC) analysis, more parameters such as start-up time and minimum up/down time are added. Here, two main approaches of the flexibility index extraction, one for ELD and another for UC analysis, are described briefly. A good view of flexibility concept formed by ρ, π and ε as the main components for each generation unit is shown in Fig. 1 [7]. These components reflect the physical constraints of each flexibility source in the power system. Thus, (ρ) is the derivative of (π) and (π) is the integral of (ρ). Equally, (π) is

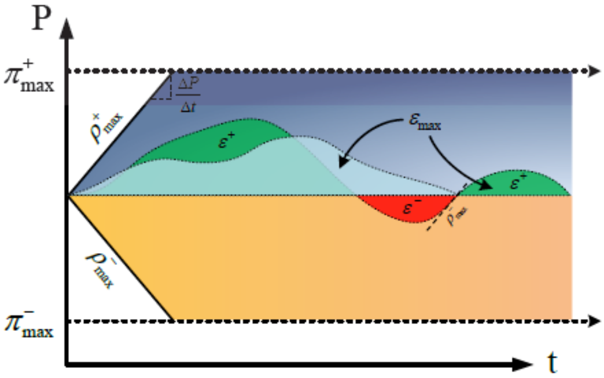


Fig. 1. Global view of flexibility concept and its limits

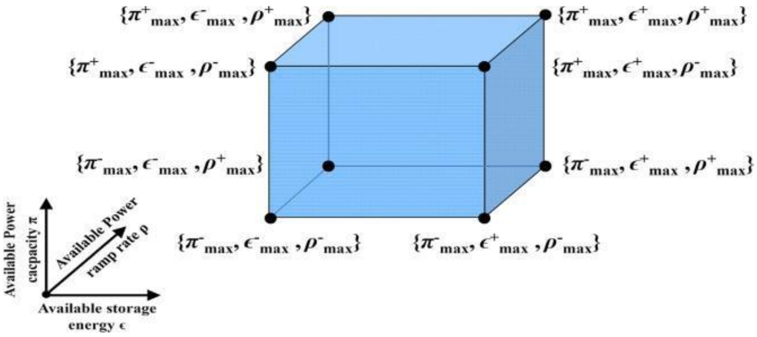


Fig. 2. The flexibility cube concept

the derivative of (ε) and (ε) is the integral of (π). Additionally, (ρ) is the line slope and (ε) is the area. This approach is similar to the flexibility area index approach. However, no idea is presented for combination of the unit flexibility indices to achieve system flexibility index.

Another approach for the flexibility index of each generating unit is determined by constructing the Composite Flexibility Metric (CFM) proposed in [8]. The flexibility index is calculated based on seven technical characteristics of the generating units, the minimum stable generation level, operating range, ramp up/down capabilities, start-up time, and minimum up and down time, all used for UC analysis. Thus, the flexibility index is calculated as:

$$flex_i = \sum_{j=1}^{K} I_{ij} w_j + \sum_{j=1}^{J} (1 - I_{ij}) w_j \tag{3}$$

Whereas $I_{i,j}$ is the normalized value of x_{ij}, each of the seven characteristics of unit i and w_j is the corresponding weighting factor. On the other hand, the first summation belongs to the characteristics, which are positively correlated with flexibility. The second summation is for the characteristics, which are negatively correlated. The combination of unit flexibility indices to achieve system flexibility follows, adding the unit indices:

$$Flex = \sum_{t=1}^{T} \sum_{i=1}^{n} flex_i u_i \tag{4}$$

u and T stand for unit state and time horizon. It is simpler than previous approach shown by (2). Although both are not acceptable and justified.

As shown in Fig.1, approach 1 is a conceptual and meaningful flexibility index and the permissible area (the area surrounded by $\pi_{max}^{+}/\pi_{max}^{-}$, $\rho_{max}^{+}/\rho_{max}^{-}$ and ε_{max}) can demonstrate the flexibility index. However, the second approach does not develop any physical and meaningful concept. In addition, the weighting factors allocation is challengeable.

A general flexibility index is provided in [2], as the cube metric similar to index presented in Fig. 1, where four parameters are used as power capacity (π), ramp-rate (ρ), energy capacity (ε) and duration of the ramp (δ) (Fig. 2). Operational flexibility can be described as the set of acceptable points surrounded by the three initial mentioned parameters. The three parameters illustrate the flexibility cube for each generation unit.

By this general overview about generation unit flexibility, a comprehensive survey of power system flexibility evaluation and indices is presented. A comprehensive overview of power system flexibility as an effective way to maintain power balance at every moment is presented in [9]. Additionally, based on the insights of the nature of flexibility, a unified framework for defining and measuring flexibility in the power system is proposes in [10]. Under the proposed framework, the latter paper proposes a flexibility metric that evaluates the largest variation range of uncertainty that the system can accommodate.

Another approach in the power system flexibility evaluation and the flexibility tracker are presented in [11]. This concept is an assessment methodology developed to monitor and compare the readiness of the power systems for high Variable Renewable Energy (VRE) shares. The flexibility tracker builds 14 flexibility assessment domains by screening systems across the possible flexibility sources (supply, demand, energy storage), and enablers (grid, markets), by 80 standardized Key Performance Indicators (KPIs) scanning the potential, deployment, research activities, policies, and barriers regarding flexibility. A comprehensive review of different flexibility measures is presented in [12]. Using suitable measures and several sources for the power system flexibility with different Variable Generation (VG) cost levels are compared in the following section. A framework to develop a composite metric providing an accurate assessment of flexibility within conventional generators of a power system is introduced in [13]. This assessment is performed, using eight technical characteristics of generating units as indicators. An Analytic Hierarchy Process (AHP) is applied to assign weights to these indicators to reflect their relative importance in the flexibility supplies. Additionally, by considering the economics and flexibility of the system that takes the flexibility of each thermal power unit into account, an optimal scheduling method is presented [14]. This method includes a multi-objective optimization scheduling model, involving the overall flexibility of the unit and the total power generation cost.

Following, some famous flexibility indices are introduced and described with more details. A flexibility index is proposed as an Insufficient Ramping Resource Expectation (IRRE), which shows the power system's inability to overcome the variability in both generation and demand sides in a certain time interval [15]. In other words, the IRRE is the expected number of instances in which the generation units in a power system cannot answer to the changes in the net load [16]. A schematic diagram is shown in Fig. 3 to explain the concept of IRRE with a concentration on wind penetration [17].

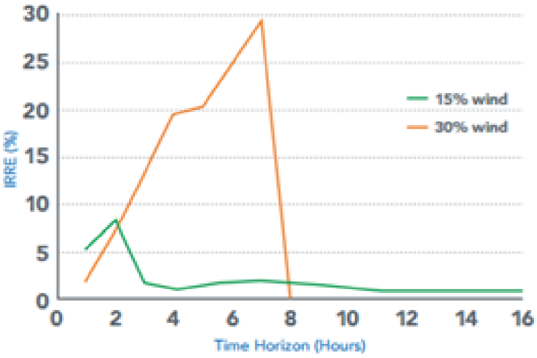


Fig. 3. Description of IRRE [17]

It is clear that by increasing the wind penetration, IRRE will increase as well. The IRRE can be used to identify the key time horizon (e.g., 2 hours in 15% wind penetration case and 7 hours in 30% case), where flexibility is an issue and an additional flexibility is required. This index is generally obtained as below [16]:

a) Calculating the net load ramping time series for the whole planning horizon in both upwards (up) and downwards (dn) directions.

b) Calculating the up/dn available flexible resources within a specified time horizon of interest (e.g. one hour), given the availability and commitment status of each generation unit, start-up time, actual production level, and total upwards or downwards ramping capabilities for the next period.

c) Aggregating all the time series for all resources to obtain the total up/dn available flexibility time series.

d) Calculating the up/dn available flexibility empirical cumulative distribution function from the total available flexibility time series.

e) Calculating the probability of insufficient ramping by substituting the required net load ramping in the obtained distribution function. The sum of the up/down probabilities time series gives the IRRE$^{+/-}$.

A conceptual flexibility index is defined in [18], which is based on four main system operation criteria as the minimum power of generation unit, the ramp rate capability, start-up time and controllability nature of the generation unit. These criteria are assigned to the system elements which are responsible for providing these criteria. Next, the flexibility measurement technique is determined by using the analytical hierarchy process (AHP) method based on these criteria. Another index is introduced in [19], as a Lack of Ramp Probability (LORP) in each up and down ramp rate characteristic. LORP can be calculated both in ramping up or ramping down situations as suggested in (5) and (6).

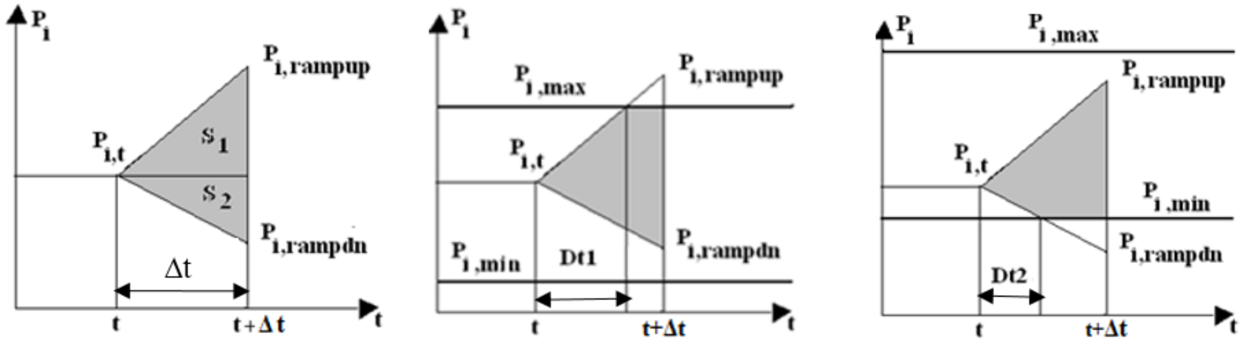
$$LORP^{up} = Pr\,\left(\sum_{i=1}^{n}\{P_{t,i} + min\,(Rampup\,\Delta t, \left(P_i^{max} - P_{t,i}\right))\} < PD_t\right) \quad (5)$$

$$LORP^{dn} = Pr\,\left(\sum_{i=1}^{n}\{P_{t,i} - min\,(Rampdn_i\,\Delta t, \left(P_{t,i} - P_i^{min}\right))\} > PD_t\right) \quad (6)$$

The concept of this index is similar to the flexibility area index, in probabilistic approach. It forms a good relation between ramp rate (ρ) and power capacity (π), as the two main components in flexibility index. Another index is defined in [20] as the System Capability Ramp (SCR). The ramping capability of a generator is defined as the ability to change its output during a specific period.

$$SCR_t = \sum_{i=1}^{n} A_{i,t}\, min\,(Rampup\,\Delta t, \left(P_i^{max} - P_{t,i}\right)) \quad (7)$$

$A_{i,t}$ shows the uncertainty of the generator taken into account, using availability and is calculated using the Markov chain-based capacity state model.



a b c

Fig. 4. Concept of flexibility area index.

The next concept which is similar to the previous index is Ramping capability Shortage Expectation (RSE), which represents the possibility of a ramping capability shortage due to major system uncertainties in a particular period [21]. The RSE is used as a criterion in the evaluation of Variable Generation (VG) acceptability. A flexibility index, named the Ramping Capability Shortage Probability (RSP) is defined in [22], which is used to quantify the extent to which the variability and uncertainty affect the flexibility.

3- FLEXIBILITY AREA INDEX CONCEPT

Detail description of the flexibility area index concept is illustrated in [3]. This concept is very similar to the concept explained in Fig.1, except excluding energy capacity (ε). Therefore, a general and brief description of the generation unit flexibility area index is presented to provide the suitable background for the achievement system flexibility index. First, suppose $P_{i,t}$ is the unit generation i at time t (Fig. 4.a).

Then at t+Δt, we have the triangle shown by $P_{i,t}$, $P_{i,rampup}$ and $P_{i,rampdn}$ where $P_{i,rampup}$ and $P_{i,rampdn}$ are the permitted up and down unit generation boundary points at time (t+Δt) which are limited by the ramp up and ramp down unit constraints. It is clear the points inside this triangle are the permitted operating points for the generation unit i in [t,t+Δt] time interval by the ramp up and ramp down constraints. The area of this triangle is defined as the unit flexibility index.

Two other limitations should be added to this triangle as up/down unit generation constraints. By the intersection of these constraints, the mentioned triangle is limited and the area corresponding to the unit flexibility index becomes smaller in Fig. 4.b and Fig. 4.c.

Here the flexibility area is calculated simply as below [3]:

a) No up/down generation constraints limitation (Fig. 4.a):

$$S = \frac{1}{2}(Rampup + Rampdn)(\Delta t^2) \triangleq S_1 + S_2 \tag{8}$$

b) If up generation constraint cuts the area ($P_{i,rampup} > P^{max}$), then S_1 reduces to (Fig. 4.b):

$$S_1 = \frac{(P^{max} - P_t)}{2}(2\Delta t - DT_1) \tag{9}$$

c) If down generation constraint cuts the area ($P_{i,rampdn} < P^{min}$), then S_2 reduces to (Fig. 4.c):

$$S_2 = \frac{(P_t - P^{min})}{2}(2\Delta t - DT_2) \tag{10}$$

It is clear that the area flexibility index includes both ramp rate capability and accessible generation interval to overcome uncertainty and variability imposed to system generation, especially by variable generations. Thus, the ramp rate (ρ) and power capacity (π) characteristics are considered here as mentioned in the first concept of flexibility index shown in Fig 1.

The main contribution of this study is to develop a suitable and acceptable routine for combining the unit flexibility indices to achieve the total system flexibility index, and also to establish a mathematical approach to validate and verify the system flexibility index performance. Although there are considerable articles about unit flexibility index, there are a few considering the extraction of system flexibility index by unit flexibility indices. As said before, [6] suggests combination of the unit flexibility indices by their capacities as the weighting factors. However, this approach is incorrect and unjustified. Since the participation of the unit flexibility indices in the system flexibility index are not necessarily proportional to the unit capacities. Where Ramp up/down unit capabilities as the most important characteristics are not proportional to the unit capacity necessarily. The simple combination illustrated in (4) is also incorrect.

Now the proposed approach for combination of the unit flexibility indices is explained. Two units with flexibility area as $flex_1$ and $flex_2$ shown in Fig. 5. Additionally, no restriction is assumed due to the maximum and minimum for both of the flexibility area indices. By considering an equivalent unit stands for these two units with the equivalent flexibility index, the equivalent triangle flexibility characteristics are as below:

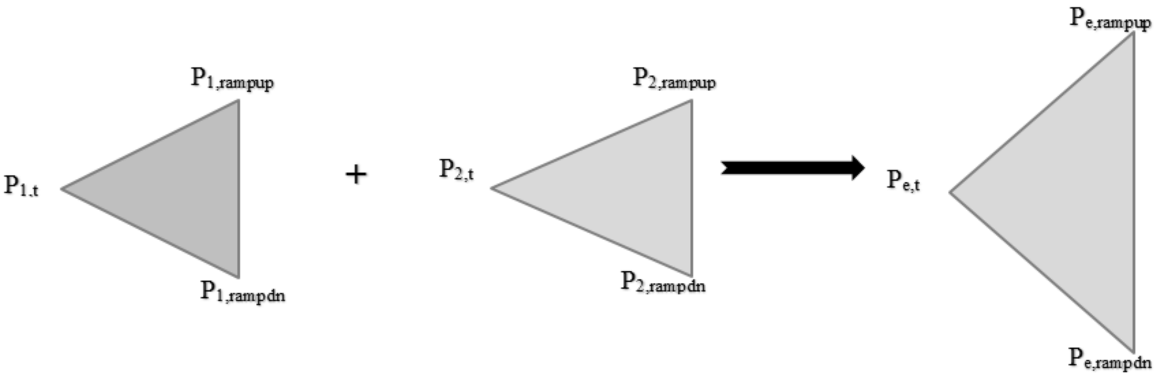
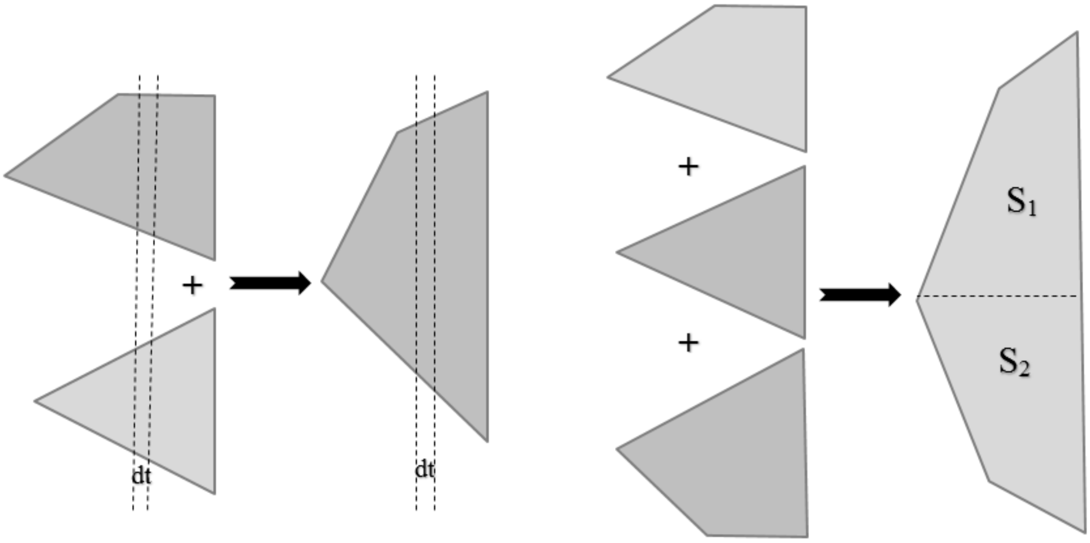


Fig. 5. Simple combination of flexibility area indices



a b

Fig. 6. Different kinds of flexibility area indices combination

$$P_{e,t} = P_{1,t} + P_{2,t} \tag{11}$$

$$Rampup_e = Rampup_1 + Rampup_2 \tag{12}$$

$$Rampdn_e = Rampdn_1 + Rampdn_2 \tag{13}$$

As can be seen the equivalent flexibility index has no linear relation to the initial units' capacities. Now the global situation is considered by adding the up/down unit generation constraints. This situation is shown in Fig. 6.a and Fig. 6.b. However, Fig.6.b can be considered as the general case.

Calculation of the equivalent flexibility area is very simple. The proposed method is a numerical routine similar to numerical integration. The partial area summation routine similar to trapezoidal algorithm in numerical integration is the simplest way to calculate equivalent area. Where the [t,t+Δt] time interval is divided by an acceptable time division as dt and the flexibility area for each unit is calculated in dt division. Later, by a simple summation for all the flexibility areas in dt division, the equivalent flexibility area is achieved. The total system flexibility index can be extracted by summation of the partial flexibility areas in dt division in [t,t+Δt] time interval. As can be seen an acceptable and justified manner is extracted for the system flexibility index considering both ramp rate (ρ) and power capacity (π) of each unit participates in the total system flexibility index. Finally, the calculated total area is divided by the number of the units to be scaled and comparable with the flexibility index introduced by (2).

Another complementary approach is to divide the flexibility area to upper and lower side with respect to the initial P at time (t) as demonstrated by S_1 and S_2 in Fig. 4.a for a single unit and Fig.6.b for the generation system. In this way, two components of the flexibility index (two partial unit/system flexibility indices) are defined. This approach is useful for understanding the source of the system flexibility reduction and also to relate each of the partial indices to the corresponding renewable (solar/wind) curtailment or the load curtailment. It is clear upper side (S_1) relates to the load curtailment and lower side (S_2) relates to the renewable curtailment. This approach is later used to verify the proposed flexibility index validity and is another contribution of this study.

4- ECONOMIC LOAD DISPATCH INCORPORATED WIND POWER

In this section, the main formulation for the economic load dispatch incorporated wind power is presented. The simplest objective function for ELD incorporated wind power can be written as:

$$Cost=\sum_{i=1}^{n}\alpha_i P(t)_i^2+\beta_i P_i(t)+\gamma_i+\sum_{i=1}^{m}d_i Pw_i(t) \quad (14)$$

Subject to:

$$\sum_{i=1}^{n}P_i(t)+\sum_{i=1}^{nt}Pw_i(t)=PD(t)+P_{loss}(t) \quad (15\text{-}1)$$

$$P_i^{min}\le P_i(t)\le P_i^{max} \quad (15\text{-}2)$$

$$\left|P_i(t)-P_i(t-1)\right|\le Rampup_i\,\Delta t \quad (15\text{-}3)$$

$$\left|P_i(t)-P_i(t-1)\right|\le Rampdn_i\,\Delta t \quad (15\text{-}4)$$

$$0\le Pw_i(t)\le P_{rated,i} \quad (15\text{-}5)$$

The relation of the wind power and the wind speed is determined by a third order polynomial function as:

$$Pw=\begin{array}{ll} 0 & v<v_{cut-in}\,,v>v_{cut-out} \\ k_w v^3 & v_{cut-in}\le v\le v_{rated} \\ P_{rated} & v_{rated}\le v\le v_{cut-out} \end{array} \quad (16)$$

Where k_w is defined as:

$$k_w=0.5n_t C_p\eta_w A\rho \quad (17)$$

The power system loss can be found by B loss coefficient method as [23]:

$$P_{loss}(t)=\sum_{i=1}^{n}\sum_{j=1}^{n}P_i(t)B_{ij}P_j(t)+\sum_{i=1}^{n}B0_i P_i(t)+B00 \quad (18)$$

As $P_{loss,t}$ depends on the $P_{i,t}$'s, then ELD solution needs an iterative method. On the other hand, because of the limitations on the up and down unit generation and the up and down ramp rates, the well-known algorithm to solve ELD is λ coefficients. Thus, Lagrange function is first formed as:

$$\begin{aligned} LG=&\sum_{i=1}^{n}\alpha_i P_{i,t}^2+\beta_i P_{i,t}+\gamma_i+\sum_{i=1}^{m}d_i P_{wi,t}- \\ &\lambda\left(\sum_{i=1}^{n}P_{i,t}+\sum_{i=1}^{m}P_{wi,t}-PD_t-P_{loss,t}\right) \end{aligned} \quad (19)$$

Partial derivatives of LG respect to $P_{i,t}$'s yields to:

$$\frac{\partial LG}{\partial P_{i,t}}=2\alpha_i P_{i,t}+\beta_i-\lambda\left(1-\frac{\partial P_{loss,t}}{\partial P_{i,t}}\right)=0 \quad (20)$$

Where:

$$\frac{\partial P_{loss,t}}{\partial P_{i,t}}=2B_{ii}P_{i,t}+\sum_{j\ne i}B_{ij}P_{j,t}+B0_i\triangleq\gamma_{i,t} \quad (21)$$

So λ_i corresponds to $P_{i,t}$ can be found as:

$$\lambda_i=\frac{2\alpha_i P_{i,t}+\beta_i}{\left(1-\gamma_{i,t}\right)} \quad (22)$$

Now the minimum and maximum λ_i should be calculated with respect to the unit limitations. Up and down limits of generation unit i are as:

$$P_{i,t}^{max}=\min\left(P_i^{max},P_{i,t}+Rampup_i\Delta t\right) \quad (23\text{-}1)$$

$$P_{i,t}^{min}=\max\left(P_i^{min},P_{i,t}-Rampdn_i\Delta t\right) \quad (23\text{-}2)$$

Thus, by substitution (23-1) and (23-2) in (22), we have:

$$\lambda_i^{max}=\frac{2\alpha_i P_{i,t}^{max}+\beta_i}{\left(1-\gamma_{i,t}\right)} \quad (24\text{-}1)$$

$$\lambda_i^{min}=\frac{2\alpha_i P_{i,t}^{min}+\beta_i}{\left(1-\gamma_{i,t}\right)} \quad (24\text{-}2)$$

In each iteration, the calculated λ is compared by the min and max limits of each unit ((24-1) and (24-2)). If each of these limits is violated, $P_{i,t}$ is fixed to the corresponding limit ((23-1) or (23-2)) and the limited generation is subtracted by the net load. Therefore, the remained net load is dispatched among other units.

Thus, it necessitates a dynamic ELD solution by changing the up and down generation limits in each iteration. The minimum and maximum of total permissible system generation constraints in time (t) can be achieved as:

$$Uplimit(t)=\sum_{i=1}^{n}P_i^{max}(t) \quad (25\text{-}1)$$

$$Dnlimit(t) = \sum_{i=1}^{n} P_i^{min}(t) \tag{25-2}$$

Thus, if the net load (demand plus loss and minus wind power) is less than Dnlimit (t), then we have wind curtailment as:

$$WC(t) = Dnlimit(t) - \left(PD(t) + P_{loss}(t) - Pw(t)\right) \tag{26}$$

And where the net load is greater than Uplimit (t), we have load curtailment as:

$$LC(t) = \left(PD(t) + P_{loss}(t) - Pw(t)\right) - Uplimit(t) \tag{27}$$

5- SOLUTION ALGORITHM

The iterative ELD solution algorithm is simple. At first some substitutions and simplifications should be done in each time step. Starting (22), we have:

$$P_{i,t} = \frac{\lambda\left(1-\gamma_{i,t}\right) - \beta_i}{2\alpha_i} \tag{28}$$

By writing (28) for all generations and then summation all the corresponding equations, we have:

$$\sum_{i=1}^{n} P_{i,t} = M\lambda + N \tag{29}$$

Where:

$$M = \sum_{i=1}^{n} \frac{1-\gamma_{i,t}}{2\alpha_i} \qquad N = \sum_{i=1}^{n} \frac{-\beta_i}{2\alpha_i} \tag{30}$$

Now we define Pdiapstch as:

$$Pdispatch = \left(PD - LC(t)\right) + P_{loss}(t) - \left(Pw(t) - WC(t)\right) = \sum_{i=1}^{n} P_{i,t} \tag{31}$$

Where the WC (t) and LC (t) are calculated from (26) and (27). The main iterative algorithm is described in four steps as below:

a) By initial assumption for P_{loss} (t) (may be zero), Pdiapstch is calculated by (31), and λ is also calculated as:

$$\lambda = \frac{Pdispatch - N}{M} \tag{32}$$

b) For each generation unit i, if calculated λ violates the max or min values as (24-1) or (24-2), $P_{i,t}$ is fixed on the corresponding limit. Where other generations are calculated by (28) and P_{loss} (t) is updated by (18). It also needs to update WC (t) and LC (t) by (26) and (27).

c) In this step, (30) and (31) are updated as (33) and (34). Where L stands for the set of limited generations.

$$M = \sum_{\substack{i=1 \\ i \notin L}}^{n} \frac{1-\gamma_{i,t}}{2\alpha_i} \qquad N = \sum_{\substack{i=1 \\ i \notin L}}^{n} \frac{-\beta}{2\alpha_i} \tag{33}$$

$$Pdispatch = \left(PD - LC(t)\right) + P_{loss}(t) - \left(Pw(t) - WC(t)\right) - \sum_{\substack{i=1 \\ i \in L}}^{n} P_{i,t} = \sum_{\substack{i=1 \\ i \notin L}}^{n} P_{i,t} \tag{34}$$

d) Convergence is checked by λ variation in two consecutive iterations. If no convergence, the algorithm is repeated from step (a) except assumption P_{loss}.

6- VERIFICATION METHOD FOR THE VALIDITY OF EQUIVALENT FLEXIBILITY AREA

Flexibility is the ability of power system to cope with the uncertainty and variability, in both generation and demand sides. Thus, the flexibility index should suitably clear this ability. In other words, by increasing the flexibility index, more ability to overcome uncertainty and variability is expected. In an especial case where the unbalance in generation/load is due to the renewable sources as large-scale wind/solar farms, wind/load curtailment or solar/load curtailment is a good measure to verify system flexibility index. By increasing the system flexibility index, less wind/load or solar/load curtailment and the other way is expected.

By a simple mathematical correlation between the mentioned parameters, one can understand the validity of the flexibility index. Pearson correlation coefficient method is a famous routine for this propose and is used here to find the correlation between the flexibility index and wind/load curtailment. Suppose X and Y as two vectors with the same dimension. Pearson correlation coefficient of X and Y is defined as:

$$\rho_{X,Y} = \frac{\sum\left(X-\mu_X\right)\left(Y-\mu_Y\right)}{\sigma_X \sigma_Y} \tag{35}$$

μ and σ are mean and standard deviation. $\rho_{X,Y}$ varies in [-1,1] interval. If X and Y are completely correlated, then $\rho_{X,Y}=\pm1$. (Plus for positively correlated and minus for negatively correlated.)

Using this criterion for the flexibility index verification, we first need enough samples of wind speed/power for ELD solution, each of them yields to the corresponding system flexibility index and also related to the wind/load curtailment. Therefore, by using the Weibull distribution density function for wind speed, the wind power samples are generated, and by running the ELD incorporated wind farm, wind/load curtailment will be calculated. On the other hand, average flexibility index and two average partial flexibility indices (S_1

Table 1. Wind farm and Weibull PDF parameters

A (m^2)	ρ (Kg/m^3)	C_p	η	n_t	d ($/MW)	v_{cut-in} (m/s)	v_{rated} (m/s)	$v_{cut-out}$ (m/s)	c	k
4000	1.255	0.4	0.8	---	1	4	12	25	8	1

Table 2. Unit flexibility and system flexibility indices

Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	System Flexibility (2)	Proposed System Flexibility
2.7778	1.9444	2.2917	1.9444	1.9444	1.9444	2.2988	2.1412

and S_2 in Fig. 6.b) are derived. The correlation between the upper partial flexibility index (S_1) and the load curtailment verifies this partial index validity. It is also true for correlation between the lower partial flexibility index (S_2) and the wind curtailment.

7- SIMULATION

As mentioned in the previous section, we need enough samples of the wind speed/power to validate the flexibility index. If we select Δt as 10 minutes, we have 144 sample in 24 hours. Using Weibull distribution density function for wind speed as shown in (36), 144 random sample data for wind speed are extracted and also corresponding 144 random data for wind power are calculated using (16).

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (36)$$

Here, simulation is performed by two test systems as six-unit and twenty-unit. The needed data for the generation system and loss coefficients for both of the test systems are presented in [23]. In each case, the wind farm parameters are the same, except the number of the wind farm units (n_t) which is selected proportional to the system generation capacity. The wind farm and Weibull PDF parameters are presented in Table 1. (n_t is different for the two mentioned test systems.)

The stochastic wind speeds are considered fixed for all simulations in the two test systems with no change. Therefore, 144 wind power samples are fixed in the two test systems. The mentioned ELD algorithm is simply implemented in MATLAB-2015 software and run on the system with Core 2 Duo processor, 2.2 Ghz, 2 GB DDR3 RAM performance. Each ELD solution is very simple and low time consuming. But should run 144 times in each load level. Thus, the total time consuming is about a few seconds for six-unit test system, but about one minute for twenty-unit test system.

6-1- Six-unit Test System

Load demand (PD) in the base case is 1263 (MW). Thus, the wind farm unit number (n_t) is considered 100 which means the rated wind power is 138.7930 (MW) about ten percent penetration. At first, an initial ELD is run without wind power incorporation. The flexibility area indices for the units are shown in Table 2. Additionally, the combination of these indices is calculated once by (2) and again by the proposed method to achieve the system flexibility index. These two system flexibility indices are shown as well.

As no flexibility reduction due to the up/down generation constraints for all units, the unit and system indices are in the maximum values. As can be seen, the system flexibility index derived by (2) is greater than the proposed index. It is for gaining the ramping up and ramping down of each unit by its capacity and where the first and third units are bigger than others in the capacity and ramp rate, system flexibility goes towards them. However, it may not be correct in general. On the other hand, the upper and lower components of the proposed flexibility index (S_1 and S_2) are 0.7986 and 1.3426. This shows that the generation system is more flexible against wind power curtailment with respect to load curtailment in this operating point. Now, the main simulation is mentioned below in three different cases. Two cases are related to load change scenarios and one case is for the wind penetration scenario.

Case 1:

As the system generation minimum and maximum constraints are 380 and 1470 (MW), PD is changed from 400 to 1400 (MW) by 50 (MW) load step. In each load step, a set of 144 stochastic wind power samples are used for 144 ELD solutions. Total wind/load curtailments are calculated by (26) and (27) in addition to the average system flexibility index for 144 wind power samples. The upper and lower components of the proposed flexibility index are calculated as well. The results are shown in Fig. 7

Average flexibility (2), shows the average flexibility index of 144 corresponding indices calculated by the combination of the unit flexibility indices by (2). While the other flexibility indices are the average of 144 corresponding indices in each load level by the proposed concept. As can be seen, the flexibility index by (2) and the proposed index have almost the same behavior. Wind curtailment decreases, but load curtailment increases by load increase. On the other hand, lower component flexibility index increases by load increase suitably in compliance with the wind curtailment reduction. However, the upper component of the flexibility index is constant and at its maximum level, except at the end part which it decreases a bit. This shows the upper component is independent from the load change. In other words, the upper component area (S_1) is never cut by the system generation up

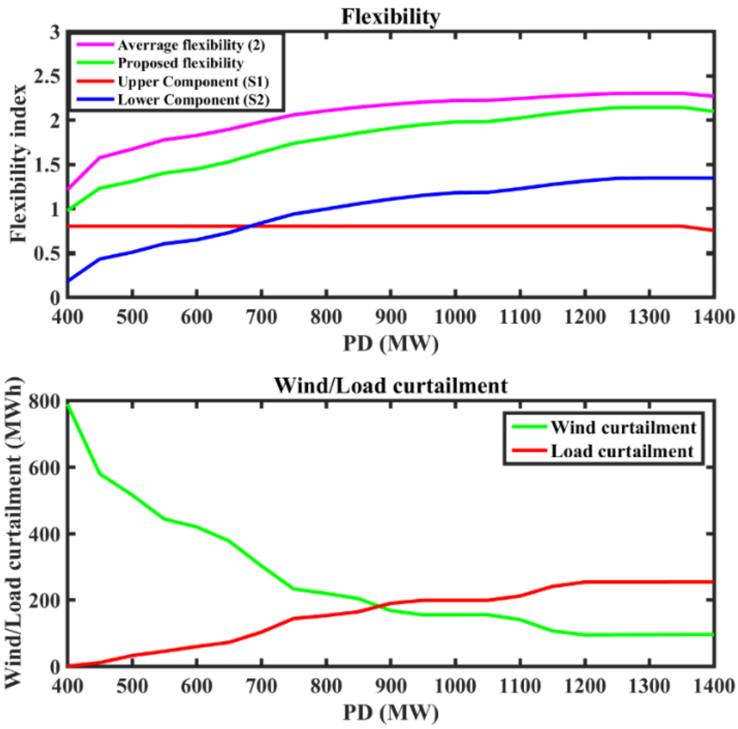


Fig. 7. Results for six-unit test system – case one

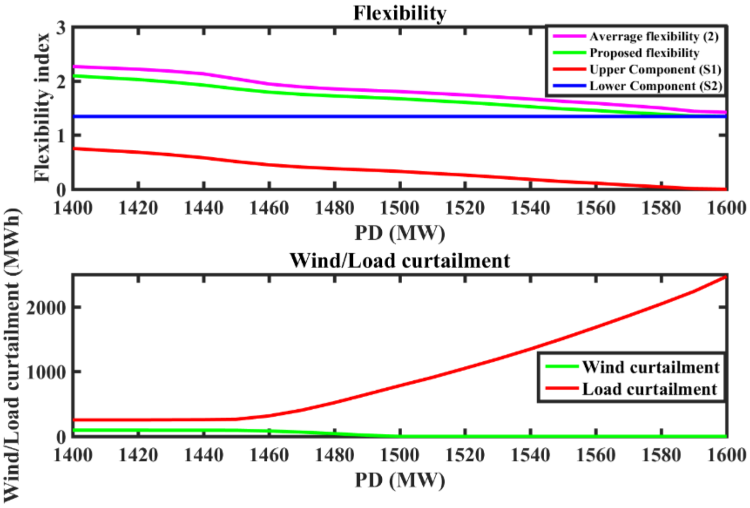


Fig. 8. Results for six unit test system – case two

limit since the net load is always less than the system load and the system capacity. Thus, the load curtailment is completely related to the lack of system flexibility due to weak ramp up capability. This should be compensated by high ramp rate generation or Energy Storage System (EES) to improve the base case system flexibility index [4].

Now the main property of the system flexibility index is verified. The correlation coefficient between the wind curtailment and the lower component of flexibility index is -0.9859, that shows a very good correlation between them. Minus sign shows the negatively correlation. On the other hand, the upper component of the flexibility index is constant. Therefore, no correlation can be found between the load curtailment and this component. The correlation coefficient between the wind curtailment and the total system flexibility index is -0.9751, which is close to the previous coefficient.

This index can be used as a suitable indicator for real time operation to show the level of system flexibility to cope with uncertainty and variability. On the other hand, if the wind/load curtailment penalties are added to the objective function, global optimization leads to the best system operation point which certainly deviates from ELD solution and with higher generation cost. Additionally, the strong correlation between the proposed flexibility index and the wind/load curtailment,

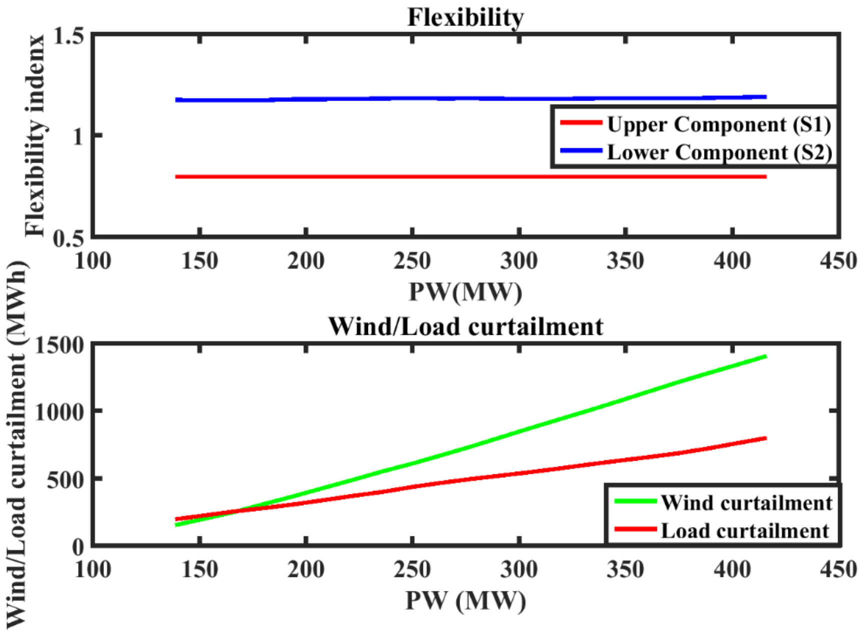


Fig. 9. Results for six-unit test system – case three

determines the economic level of the flexibility index which differs from one system to another and from one load level to another. This means the economic trade-off between generation cost and flexibility cost (flexibility value) as mentioned earlier.

Case 2:

To achieve considerable change in the upper component of the flexibility index, PD is changed from 1400 to 1600 (MW) by 10 (MW) load steps, where the net load is expected to be more than the system generation capacity. Similar results as the previous case are shown in Fig. 8.

Here, the upper component of flexibility index has considerably decrease, while another component is almost constant and equal to its maximum value. Wind curtailment is small and near zero, which shows enough lower component system flexibility. Unlike the previous case, the ramp down and minimum generation system capabilities are suitable to respond to sudden increase in the wind power to prevent wind curtailment. But load curtailment has a large increase. The correlation coefficient between the load curtailment and the upper component of flexibility index is -0.9653, which shows a good correlation. Additionally, the correlation between the load curtailment and the total system flexibility index is -0.9653 which is the same as the previous one since the lower component of the flexibility is constant.

It should be noted that the load increase will cause increase in the lower component of the flexibility index and decrease in the wind curtailment. Where the upper component of the flexibility index decreases and the load curtailment increases by load increase as can be seen in Fig. 7 & Fig. 8.

Case 3:

In the third case, by considering PD as 1000 (MW) and constant, the wind power penetration has changed. This is performed by changing the n_t from 100 to 200 by 5 increase in each step. The mentioned ELD simulation in each of the wind power penetration is performed. The results are shown in Fig. 9. Horizontal axis shows the rated wind power. Only two components of the flexibility index are shown which are constant without no change and equal to their corresponding maximum value. This shows the saturation of system flexibility and the most capability of the system generation. Thus, no correlation between the wind/load curtailments and the lower/upper components of the flexibility index can be found. On the other hand, the correlation coefficients between the wind power penetration and the wind/load curtailments are 0.9993 and 0.9995, which show completely dependency where the system flexibility index is constant.

However, as can be seen in Fig. 9, both the wind/load curtailments increase by the wind power penetration increase which shows the lack of system flexibility to overcome wind power uncertainty and variability. Thus one can find the best level of system flexibility to limit the wind/load curtailments with different wind power penetration. In other words, the permitted wind power penetration can be found to limit the wind/load curtailments to the desired values. On the other hand, the adequate system flexibility can be found to respond to the desired penetration by improving base case flexibility, adding high ramp rate generations or energy storage systems.

6-2- Twenty-unit Test System

A larger test system is considered to show the performance of the proposed concept. Load demand (PD) in the base case is 1500 (MW). Since the maximum capacity of this system is 3865 (MW), the wind farm unit number (n_t) is considered 200. In addition, first an initial ELD is run without the wind power incorporation. The system flexibility index calculated by (2) and also by the proposed index are as 1.0804 and 0.7882.

The difference between the base case flexibility indices for

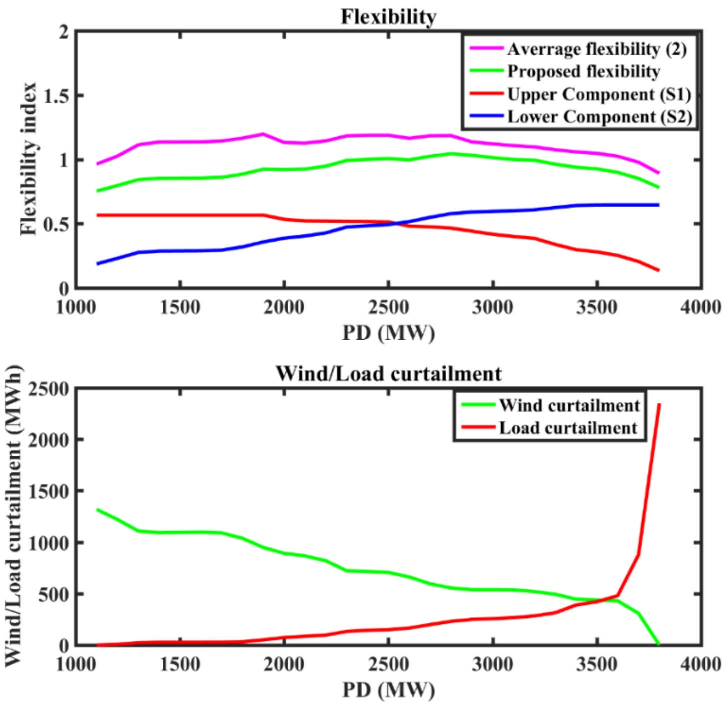


Fig. 10. Results for twenty-unit test system

the two test systems is noticeable. As said before, the flexibility index helps to compare the two system flexibility levels and their ability of to cope with uncertainty and variability. Thus, it is clear that the first test system is more flexible than the other test system.

The system flexibility index by (2) is more than the proposed index, similar to the previous test system. As the system generation minimum and maximum constraints are 1010 and 3865 (MW), PD is changed in 1100 to 3800 (MW) by 100 (MW) load step for similar simulation as the previous test system. The similar results of this simulation are shown in Fig. 10. In addition, the flexibility index by (2) and the proposed flexibility index have almost the same behavior.

Here the correlation is much more clear, especially for the load curtailment. Additionally, the correlation between the lower component of the flexibility index and wind curtailment can be verified. Where the correlation coefficient is -0.9659 which is very good. The correlation coefficient between the upper component of the flexibility index and the load curtailment is -0.8031 which is also good, but not as good as the previous one. It is for the sudden increase in the load curtailment in high load levels. If we calculate this correlation coefficient in two load intervals as [1100,3500] and [3500,3800] (before and after the sudden increase) separately, we get -0.9796 and -0.9572 which show a very good correlation in each case.

The upper/lower component decreases/increases continuously. The upper component is in its maximum value in the low load level and then decreases, but the lower component increases with the load level increase and approaches to its maximum value in the high load level. Thus, the flexibility index increases in the low load levels and then decreases. The maximum values of the upper and lower components don't occur simultaneously. The maximum values of these components in this simulation are 0.5660 and 0.6458. The biggest value of the flexibility index in this simulation is 1.0428 in 2800 (MW) load level. Where the minimum value of the sum of the wind/load curtailments occurs in this load level as 785.5359 (MWh). This shows a good dependency between the proposed flexibility index and the wind/load curtailments, and verifies the concept of economic trade-off illustrated in the previous test system.

8- CONCLUSION

The power system flexibility evaluation requires suitable system flexibility index to show the level of system flexibility. The system generation capacity and ramp rate capability are the two main features which are originated from the characteristics of generation units. Therefore, the system flexibility index should be achieved by the unit flexibility indices. In this study, using the concept of flexibility area index for generation unit flexibility, an acceptable and justified method was introduced to achieve the system flexibility index. Where the wind/load curtailment is used to evaluate the performance of this index and its capability to clear generation/load unbalance due to the weakness of the power system flexibility. This way the proposed flexibility index is decomposed into two partial indices reflecting the system flexibility against the wind/load curtailment. Thus, it clears which ramp up and maximum generation capabilities or ramp down and minimum generation capabilities may be inadequate, which should be compensated by suitable tools such as high ramp rate generations or energy storage systems. As the simple and fast calculation of this index, it can be easily used for real time operation as the power system flexibility indicator.

Since the proposed index is strongly correlated to the wind/load curtailment, it can be easily converted to economic value (cost) corresponding to the wind/load curtailment penalties to be compared with other system costs. Therefore, an economic trade-off can be established to show the best level of system flexibility for minimum system cost including the operation and flexibility cost. Where the flexibility index is decomposed to up/down components, different flexibility cost can be allocated to each of these components with regard to their importance.

Sensitivity analysis is also another advantage of this concept to show the most important units participating in the system flexibility index and the up/down components, mainly by changing the ramp rate capability of the units around their nominal value (may be %±10). Additionally, this sensitivity analysis may be performed to the wind power penetration to show the desirable penetration factor to achieve an acceptable system flexibility level.

Finally, another future work in this field is to combine the energy storage flexibility area index as described in [4] with the unit flexibility indices to achieve the total system flexibility index and also to show the impact of energy storage in the power system flexibility improvement. This approach can be used to calculate the needed energy storage capacity to improve the system flexibility index to the acceptable level.

NOMENCLATURE

A: turbine area, m^2
B, B0, B00: power loss coefficients
c: scale factor of weibull function
Cost: total cost function, $
C_p: power coefficient for wind turbine
d: wind power operation cost, $/MW
Dt_1: intersection of P^{max} and Rampup constraints, hour
Dt_2: intersection of P^{min} and Rampdn constraints, hour
flex: unit flexibility index
Flex: system flexibility index
k: shape factor of weibull function
k_w: nonlinear wind power coefficient
n_t: number of wind turbines
P: unit generation, MW
P_{loss}: system loss, MW
P^{max}: maximum unit generation, MW
P^{min}: minimum unit generation, MW
P_{rated}: wind farm nominal power, MW
Pw: wind power, MW
PD: load demand, MW
Rampdn: unit ramp down rate constraint, MW/hour
Rampup: unit ramp up rate constraint, MW/hour
S: area corresponds to flexibility, MW*hour
S_1: upper side of flexibility area, MW*hour
S_2: Lower side of flexibility area, MW*hour
v: wind speed, m/s
v_{cut-in}: starting wind speed, m/s
$v_{cut-out}$: shut down wind speed, m/s
v_{rated}: nominal wind speed, m/s
Δt: time step, hour

Greek symbols

α, β, γ: thermal unit operation cost coefficients, $\$/MW^2$,$/MW,$
η_w: wind turbine-generator efficiency
ρ: air density, kg/m^3

Subscript

e: equivalent
i: counter
t: time
n: number of thermal units
m: number of wind farms

Superscript

max: max value
min: min value

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