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Assessing Increased Flexibility of Energy Storage and Demand Response to Accommodate a High Penetration of Renewable Energy Sources

Ahmad Nikoobakht, Jamshid Aghaei, *Senior Member, IEEE*, Miadreza Shafie-khah, *Senior Member, IEEE,* and João P. S. Catalão, *Senior Member, IEEE*

***Abstract*—Today's power systems are subject to various challenges arising from the large-scale integration of renewable energy sources (RES), especially wind energy production (WEP). System flexibility, or the capability of a system to address deviations in variable RES production, is becoming more and more relevant. This paper aims to provide a systematic approach to evaluate the level of flexibility of a power system by unequivocally considering fast-ramping units (FRU), hourly demand response (DR) and energy storage (ES). In addition, to research the flexibility role in power system operation, an 'online' index is considered to evaluate the technical aptitude of the FRU, hourly DR and ES system to deliver the required flexibility. The mathematical representation of day-ahead scheduling, with the added modeling of an online flexibility index, is a mixed-integer nonlinear program (MINLP). This paper presents a method to convert this MINLP into a mixed-integer linear program (MILP) without loss of accuracy. The adapted 6-bus and IEEE 118-bus systems are employed to assess the suggested models and flexibility metric, demonstrating the proficiency of the online flexibility index.**

***Index*—Demand response, energy storage, flexibility, renewable energy sources, uncertainty.**

NOMENCLATURE

A. Indices and Sets

$(\cdot)^s$ Related to scenario $s=\pm$, "+" and "–" refer to the upper and lower boundaries of possible wind uncertainty, respectively.

g,w,d,e Index for units, wind units, demand and storage, respectively.

$g(n),w(n),e(n)$ Set of units, winds and storages associated to bus *n*.

n Bus index.

k Transmission line index.

t Time periods indices.

$k(n,m)\,/\,k(m,n)$ Set of line with n as "to"/"from" bus *m*.

B. Constants

$P_g^{max}\,/\,P_g^{min}$ Max/min capacity of unit *g*.

$D_d^{max}\,/\,D_d^{min}$ Max/min capacity of demand *d*.

$RU_d\,/\,RD_d$ Maximum load pick-up/drop-down rate of flexible demand *d* [MW/h].

$\bar{P}_e^c\,/\,\underline{P}_e^c$ Max/min charge of storage *e*.

$\bar{P}_e^c\,/\,\underline{P}_e^c$ Max/min discharge of storage *e*.

$R_{(\cdot)}^{up}\,/\,R_{(\cdot)}^{dn}$ Max ramp up/down capability of the flexible recourse (MW/(10 min)).

$E_e^{\max}\,/\,E_e^{\min}$ Maximum energy change of the ES system *e*.

K_g^{SU} Start-up cost of unit *g* [$/MWh].

P_k^{max} Maximum power flow of line *k*.

$P_{w,(\cdot)}^{(\cdot)}$ Forecasted wind power output of unit *w*.

M Separative factor; a large positive number.

$B_{(\cdot)}$ Admittance of line *k*.

$E_{(\cdot)}^{max}$ Maximum energy change of demand in the scheduling horizon.

$\bar{\Delta}R_g^u\,/\,\underline{\Delta}R_g^d$ Maximum ramp up/down limits of unit *g*.

$\bar{\Delta}R_d^u\,/\,\underline{\Delta}R_d^d$ Maximum ramp up/down limits of demand *d*.

$\bar{E}_e\,/\,\underline{E}_e$ Max /min state of storage *e*.

η_e ES system *e* charge efficiency.

TC_b Cost threshold linked with response time ($).

ξ Critical percent of objective function used in cost threshold.

$C_g^s\,/\,C_d^s$ Marginal production cost of unit/demand *g*/*d* in scenario s [$/MWh].

$C_g^0\,/\,C_d^0$ Marginal production cost of unit/demand *g*/*d* in base case [$/MWh].

V_d^{LOL} Value of lost load for demand *d* [$/MWh].

Δt Response time window.

C. Variables

$P_{g,(\cdot)}^{(\cdot)}\,/\,P_{e,(\cdot)}^{(\cdot)}$ Power generation of (unit *g*)/(energy storage *e*).

$Pc_{et}^{(\cdot)}\,/\,Pd_{et}^{(\cdot)}$ Charge/discharge power of the ES system *e* at time *t*.

$En_{et}^{(\cdot)}$ Net discharged energy of the ES system *e* at time *t*.

$E_{e,t}^{(\cdot)}$ Available energy in ES system *e* at time *t*.

$uc_{e,t}^{(\cdot)}\,/\,ud_{e,t}^{(\cdot)}$ Charging/discharging mode of ES system.

$\Delta F_{(\cdot)t}^{up}\,/\,\Delta F_{(\cdot)t}^{down}$ Maximum ramp up/down that can be provided by a flexible resource at time *t*.

C_{gt}^{SU} Cost due to start-up of unit *g* [$] in period *t*.

$\bar{\Delta}r_{gt}^s\,/\,\underline{\Delta}r_{gt}^s$ Deployed up/down-reserve by unit *g* in period *t* and scenario *s* [MW].

$\bar{\Delta}r_{dt}^s\,/\,\underline{\Delta}r_{dt}^s$ Deployed up/down-reserve by demand *d* in period *t* and scenario *s* [MW].

$FR_{(\cdot)}$ Flexible resource.

$LC_{(\cdot)}^{(\cdot)}$ Curtailment load.

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A. Nikoobakht is with the Higher Education Center of Eghlid, Eghlid, Iran- (email: a.nikoobakht@eghlid.ac.ir).

J. Aghaei is with the Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, Iran (e-mail: aghaei@sutech.ac.ir).

M. Shafie-khah is with C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal (e-mail: miadreza@ubi.pt).

J.P.S. Catalão is with INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal, also with C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal, and also with INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1049-001, Portugal (e-mail: catalao@ubi.pt).

SFI	System flexibility index.
u_{et} / u_{gt}	Binary variable for state of (ES system e) /(unit g) at time t.
$u_{d,(\cdot)}$	Binary variable for demand d.
$\theta_{k,(\cdot)}^{(\cdot)}$	Phase angle of line k.
α	Wind uncertain robust radius of uncertainty.
TC	Total operation cost [$]
$P_{w,(\cdot)}^{s}$	Wind power output of unit w in scenario s.
D_{dt}^{0}	Base case hourly demand.
Ψ,Φ	Non-negative continuous variables
U	Binary variable, on/off status of each flexible resource.
μ	Vector of system flexibility index (SFI) for 24h.
$\bar{C}$	Cost threshold.

D. Abbreviations

SFI	System flexibility index.
WEP	Wind energy production.
FR	Flexible resource.
DR	Demand response.
FRU	fast-ramping units.
ES	Energy storage.

I. Introduction

A. Motivation and Approach

One characteristic that variable renewable energy sources (RESs) have in common is an output dominated by atmospheric conditions [1]. Although most RESs have a noteworthy evolution in installed capacity in recent years, the growth of wind energy is especially remarkable [1].

Wind energy production (WEP) may consequently be hard to predict over specific time scales. Accordingly, high penetration of variable WEP dramatically augments the variability and uncertainty in power system's generation output [2]. This entails the ability of the system to respond to unexpected changes, accommodating a new status in an acceptable time frame with reasonable cost.

In [3], the meaning of flexibility is recognized, although its concept is not clear and duly quantified. Consequently, the notion of flexibility has drawn attention lately, both in the academia in power systems studies and in industry reports, with the aim of taking decisive steps in its definition and proper assessment for operation and planning studies [4], [5], [6], [7]. However, important questions as how much flexibility a resource provides and how we can estimate the level of flexibility in a power system still lack answers. In the literature, significant efforts have been made to evaluate system flexibility level [6], [7], [8].

For example, in [7], flexibility is defined and measured as the "*ability to accommodate the variability and uncertainty in load-generation balance while sustaining satisfactory levels of reasonable operating costs and system reliability*". This reference provides an "offline" index to evaluate the technical ability of individual thermal units and the overall generation mix to provide the wanted flexibility. This index is not influenced by operational decisions, so it entails a simple method to measure the ability of the power system to handle RESs. Similarly, flexibility is given in [8] as "*the ability of a system to deploy its resources to respond to changes in netload*". In this reference, a probabilistic index is proposed for system planning.

The probabilistic index evaluates the system's capability to endure a certain security or reliability criteria in a probabilistic manner, e.g., this reference proposes an insufficient ramping resource expectation (IRRE) to evaluate system flexibility, similar to what LOLE represents for capacity adequacy.

Most proposed techniques to evaluate the system flexibility are founded on multitemporal simulations of the power system operation [7], [9]. Also, in the most of recent literature, an online and intuitive index is not proposed to system flexibility metric. In addition to an "offline" index for flexibility, it is also imperative to have "online" evaluation metrics able to provide assessments of "how flexible a power system is", thus allowing to straightforward compare the technical flexibility of different systems having various flexible resources (FRs).

Evaluating the impact of FRs on system flexibility implies searching for quantitative metrics. Indeed, a quantitative metric, which could be used "online" to appraise the level of flexibility of a system and the contribution of each individual flexible resource to the whole system flexibility, is not only desirable but also valuable. Accordingly, this paper provides an online metric for measuring the flexibility level at both individual level and system wide level. This online metric evaluates the capability of a system to address the flexibility requirements arising from the uncertainty and variability of WEPs.

Generally, the system flexibility in traditional power systems has been dominated by thermal units. In contrast, in today's power systems are increasingly admitting various flexible resources, i.e., fast-ramping unit (FRU) and hourly demand response (DR) and energy storage (ES) system, to help mitigate the impact of variability and uncertainty arising from higher penetration levels of WEPs.

The three main types of flexible resources are the FRU, ES system and hourly DR program. Such flexible resources are capable of providing ample ramping. The flexibility available from a generator, interconnection resource, or the ES system and hourly DR is, in turn, reliant on its production schedule and network location.

Network congestion significantly affects the scheduling of flexible resources and modifies the flexibility availability [2], [10], [11]. This association between a resource's flexibility and its location has been recognized by operators when deciding the reserve needs for the unforeseen outage events [5]. The FRU, generating units who can rapidly startup or shutdown within the required time interval, usually less than one hour, could also deliver up/down ramping capability and upward/downward wind power uncertainty following [12], [13]. However, with the recent increase in hourly DR [5], [14], [15], [16], [17], [18], flexible demands can also participate in increasing the amounts of WEPs integration. The contribution of flexible demand in offering flexibility from the system's operator point of view is discussed in [5], [13].

In [13], the hourly DR program enabled by smart grid computational tools would adapt electricity consumption patterns to benefit customers from having low-priced electricity during the off-peak hours, as customers have a more active role in the power system operation. Moreover, hourly DR provides other potential advantages such as lower volatilities in market prices, augmented system reliability, and a lesser probability for market power. The most resourceful dynamics of the power market would be attained by joining the flexible generation with flexibility at the demand side.

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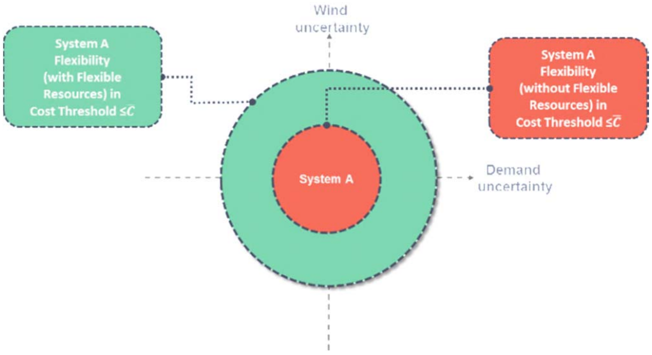

Fig.1. System flexibility with wind and demand uncertainty.

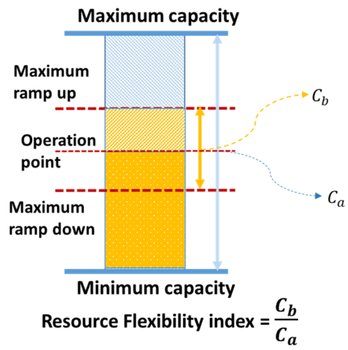

Fig. 2. Dispatching of flexible resource in its max/min capacity and metric to quantify the resource flexibility index.

In addition, most researchers agree that ES system is cardinal to a renewable energy future. The ES system will not only help to support shortfalls between supply and demand, but also provide flexibility in the operation and management of the WEPs uncertainty [19], and [20].

The ES systems provide a two-fold advantage in power systems with WEPs, firstly it reduces the ramp up/down stress on conventional thermal units induced by WEPs and secondly it reduces the up-/down-ramping requirements [20]. Thus, a power system should have enough flexible resources in its operation to endure higher integration levels of WEPs [13], [21].

More variability and uncertainty can be endured by a more flexible system, so higher WEPs levels can be attained [2], [5], [21]. Higher system flexibility is achieved with flexible generation, FRU and demand, and also flexible energy storage (when available). So, the core focus of this paper is the effect of FRU, flexible demand and energy storage system in the management of WEPs uncertainty. Maximizing level of system flexibility for a cost limitation with coordinated available flexible resources, i.e., fast-ramping unit, hourly DR and ES system, in a power system, is our aim in this paper.

For example, in Fig.1, the variation range of uncertainties under a given cost threshold are represented by the size of the circles. As illustrated in the figure, the red circle is the greatest uncertainties variation range inside which “system A” can remain feasible for cost threshold $\bar{C}$, without flexible resources. Green circle is the same system with flexible resources, as can be seen in this figure, with more increase size of the green circle than the red circle it can be said that flexible resources, in “system A”, could provide more system flexibility in same (or less) cost threshold $\bar{C}$.

B. Contributions

The contributions of this paper are twofold:

- To propose a novel methodology to estimate the flexibility of a given day-ahead scheduling model, considering multiple types of flexible resources (including FRU, hourly DR and ES system), which can be modeled using mixed integer linear programming (MILP).

- To maximize the level of flexibility satisfying the operation cost constraint in a system with high penetration of WEPs, using simultaneously coordinated flexible resource options, including hourly DR, ES system, FRU, and up/down ramping capability of these resources.

To the best of the authors’ knowledge, no reference has provided a maximum level of system flexibility with flexible resources considering WEP uncertainty.

II. Resources and System Flexibility Metrics

This paper provides a metric to measure the flexibility level at both the individual level and system wide level. This metric quantifies the aptitude of a system to manage the flexibility requirements arising from the uncertainty and variability associated to WEPs.

Each flexible resources, i.e., conventional thermal unit, fast-ramping unit, demand and ES system, can be employed to meet the requirement of system flexibility. Conventional thermal units can deliver upward WEPs following and upward reserves, and the contribution is restricted by ramp-up rate and the additional capacity between the scheduled output and the maximum capacity (as shown in Fig. 2.).

Likewise, as can be seen in Fig.2, its ramp-down rate and the difference between scheduled output and their minimum capacity generation restrain its capability to offer downward WEPs following and downward ramping. Given that the constraints to provide hourly WEPs following and upward reserve are alike, we take the constraints for delivering reserve as an example.

They can be given as follows:

$$\Delta F_{gt}^{up} = \min\left\{P_g^{\max} - P_{gt}, R_g^{up}\cdot\Delta t\right\} \tag{1}$$

$$\Delta F_{gt}^{down} = \min\left\{P_{gt} - P_g^{\min}, R_g^{down}\cdot\Delta t\right\} \tag{2}$$

Here, ΔF_g^{up} and ΔF_g^{down} represent the maximum up/down ramping that can be offered by conventional thermal unit g at hour t. Also, the hourly DR can provide ramp-up and –down to WEPs following as similar to the conventional thermal unit and fast ramping unit. Mathematically, demand side flexibility can be summarized as follows:

$$\Delta F_{dt}^{up} = \min\left\{D_d^{\max} - D_{dt}, R_d^{up}\cdot\Delta t\right\} \tag{3}$$

$$\Delta F_{dt}^{down} = \min\left\{D_{dt} - D_d^{\min}, R_d^{down}\cdot\Delta t\right\} \tag{4}$$

In addition, maximum ramp-up/–down for the ES system is calculated similar to (1) and (2), respectively.

$$\Delta F_{et}^{up} = \min\left\{E_e^{\max} - E_{et}, R_e^{up}\cdot\Delta t\right\} \tag{5}$$

$$\Delta F_{et}^{down} = \min\left\{E_{et} - E_e^{\min}, R_e^{down}\cdot\Delta t\right\} \tag{6}$$

The influence of each resource to the flexibility of the system is thus limited by its deployable range. Thus, the capability of the system to track the WEP uncertainty and meet the demand balance constraint should be limited by maximum ramping capabilities and adaptable capacity.

From (1) and (2), the up- and down- ramp rates capabilities and the difference between the minimum and the maximum capacity of flexible resources are the variables and parameters that outline its capability to deliver flexibility. Accordingly, a flexibility index can be specified for each flexible resource. This index should be normalized as indicated next to account for different flexible resources sizes:

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$$\begin{cases} FR_{gt} = \dfrac{\Delta F_{gt}^{up} + \Delta F_{gt}^{down}}{P_g^{\max} - P_g^{\min}} \\ FR_{dt} = \dfrac{\Delta F_{dt}^{up} + \Delta F_{dt}^{down}}{D_d^{\max} - D_d^{\min}} \\ FR_{et} = \dfrac{\Delta F_{et}^{up} + \Delta F_{et}^{down}}{E_e^{\max} - E_e^{\min}} \end{cases} \quad (7)$$

where FR_{gt} , FR_{dt} and FR_{et} designate the speed at which a flexible resource (FR) can regulate their output inside max and min capacity. Overall system flexibility is given as:

$$SFI = \sum_t \left(\frac{\sum_g \left(\Delta F_{gt}^{up} + \Delta F_{gt}^{down}\right) + \sum_d \left(\Delta F_{dt}^{up} + \Delta F_{dt}^{down}\right) + \sum_e \left(\Delta F_{et}^{up} + \Delta F_{et}^{down}\right)}{\sum_g \left(P_g^{\max} - P_g^{\min}\right) \cdot u_{gt} + \sum_d \left(D_d^{\max} - D_d^{\min}\right) \cdot u_{dt} + \sum_e \left(E_e^{\max} - E_e^{\min}\right) \cdot u_{et}} \right) \quad (8)$$

III. Linearization of System Flexibility Index

In (8), the system flexibility index (*SFI*) index is a nonlinear function. For this reason, solving the day-ahead scheduling problem with *SFI* index may not be tractable, even for small size systems.

This paper presents a method to convert this nonlinear function into a mixed-integer linear program (MILP) without loss accuracy.

The linearization of the *SFI* index has been calculated as follows:

$$\sum_t \sum_g \left(P_g^{\max} - P_g^{\min}\right) \cdot u_{gt}.SFI + \sum_t \sum_d \left(D_d^{\max} - D_d^{\min}\right) \cdot u_{dt}.SFI$$
$$+ \sum_t \sum_e \left(E_e^{\max} - E_e^{\min}\right) \cdot u_{et}.SFI \quad (9)$$
$$= \sum_t \left(\begin{array}{l} \sum_g \left(\Delta F_{gt}^{up} + \Delta F_{gt}^{down}\right) + \\ \sum_d \left(\Delta F_{dt}^{up} + \Delta F_{dt}^{down}\right) + \sum_e \left(\Delta F_{et}^{up} + \Delta F_{et}^{down}\right) \end{array} \right)$$

The linearized form of the left side of term (9) is shown in (10)-(11) in which the lower and upper bounds of the continuous variable are considered as zero, and a large number, *M*, respectively. Here, Φ and Ψ are nonnegative continuous variables.

$$\Phi = U\mu, \quad U \in \{0,1\} \quad (10)$$

$$\Phi = \mu - \Psi \quad (11)$$

$$0 \le \Phi \le M \cdot U \quad (12)$$

$$0 \le \Psi \le M \cdot (1-U) \quad (13)$$

The binary variable U is a vector of commitment related decisions including the on/off status of each flexible resource for each interval of the considered period, usually 24 h n an ISO setting. The continuous variable μ is a vector of system flexibility index (SFI) for 24h.

IV. Assessing the System Flexibility for a Day-Ahead Scheduling Problem

A. *Day-Ahead Scheduling Model*

This section describes in detail all constraints used in the proposed day-ahead scheduling problem incorporating hourly DR and ES system model. Accordingly, the proposed formulation for day-ahead scheduling problem with this flexible resources is addressed in the following subsections by (14)–(40). In these formulations, the total cost (TC) of the day ahead scheduling problem is deemed as the objective function as mentioned in (14), which is subject to the first stage and second stage constraints, (15)-(27) and (28)-(40), respectively.

$$\min TC = \sum_t \left\{ \begin{array}{l} \sum_g \left(C_g^0 \cdot P_{gt}^0 + C_{gt}^{SU}\right) - \sum_d \left(C_d^0 D_{dt}^0\right) \\ + \sum_g C_g^s \left(\underline{\Delta} r_{gt}^s + \bar{\Delta} r_{gt}^s\right) + \sum_d \left(C_d^s \left(\underline{\Delta} r_{dt}^s + \bar{\Delta} r_{dt}^s\right) + V_d^{LOL} LC_{dt}^s\right) \end{array} \right\} \quad (14)$$

The objective function entails two main parts: first-stage and second stage parts. The first stage part refers to offered generation cost plus start-up and shutdown costs and the utilities of the flexible demands at the normal condition. Besides, the second stage part mentions the cost of power adjustments for the thermal unit, flexible demand and involuntary load curtailment in stress condition (or the wind uncertainty).

$$\sum_{g(n)} P_{gt}^0 + \sum_{w(n)} P_{wt}^0 + \sum_{e(n)} P_{et}^0 - \sum_{k(n,m)} B_{nm} (\theta_{nt}^0 - \theta_{mt}^0) = D_{dt}^0 \quad (15)$$

$$K_g^{SU} (u_{gt} - u_{g,t-1}) \le C_{gt}^{SU} \quad (16)$$

$$u_{gt} P_{gt}^{\min} \le P_{gt}^0 \le u_{gt} P_{gt}^{\max} \quad (17)$$

$$D_d^{\min} u_{dt} \le D_{dt}^0 \le D_d^{\max} u_{dt} \quad (18)$$

$$RD_d \le D_{dt}^0 - D_{d,t-1}^0 \le RU_d \quad (19)$$

$$-\bar{P}_e^c \cdot uc_{et} \le Pc_{et}^0 \le -\underline{P}_e^c \cdot uc_{et} \quad (20)$$

$$\underline{P}_e^d \cdot ud_{et}^0 \le Pd_{et}^0 \le \bar{P}_e^d \cdot ud_{et}^0 \quad (21)$$

$$En_{et}^0 = \eta_e \cdot Pc_{et}^0 - Pd_{et}^0 \quad (22)$$

$$P_{et}^0 = Pc_{et}^0 + Pd_{et}^0 \quad (23)$$

$$E_{e,t}^0 = E_{e,t-1}^0 - En_{e,t}^0 \quad (24)$$

$$E_e^{\min} u_{et} \le E_{e,t}^0 \le E_e^{\max} u_{et} \quad (25)$$

$$E_{e,0} = E_{e,24} \quad (26)$$

$$uc_{e,t}^0 + ud_{e,t}^0 \le u_{et} \quad (27)$$

Constraint (15) represents the power balance at the normal condition stage, where the thermal unit, ES system and flexible demand schedules are determined. The start-up costs are modeled by (16), which depend on the on/off status of each unit using a binary variable. Other unit constraints include minimum on/off time, ramping up/down rate. The limits of thermal unit generation and flexible demands at the normal condition are represented by (17) and (18), respectively. Constraint (19) enforces the pick-up/drop-down rate bounds of flexible demands at the normal condition. The pick-up/drop-down rates denote how consumption is increased or decreased in a flexible load.

$$\sum_{g(n)} P_{gt}^s + \sum_{w(n)} P_{wt}^s + \sum_{e(n)} P_{et}^s - \sum_{k(n,m)} B_{nm} (\theta_{nt}^s - \theta_{mt}^s) = D_{dt}^s - LC_{dt}^s \quad (28)$$

$$P_{gt}^s = P_{gt}^0 + \bar{\Delta} r_{gt}^s - \underline{\Delta} r_{gt}^s \quad (29)$$

$$D_{dt}^s = D_{dt}^0 + \bar{\Delta} r_{dt}^s - \underline{\Delta} r_{dt}^s \quad (30)$$

$$0 \le \bar{\Delta} r_{gt}^s \,/\, \underline{\Delta} r_{gt}^s \le \bar{\Delta} R_g^u \,/\, \underline{\Delta} R_g^d \quad (31)$$

$$0 \le \bar{\Delta} r_{dt}^s \,/\, \underline{\Delta} r_{dt}^s \le \bar{\Delta} R_d \,/\, \underline{\Delta} R_d \quad (32)$$

$$-\bar{P}_e^c \cdot uc_{et}^s \le Pc_{et}^s \le -\underline{P}_e^c \cdot uc_{et}^s \quad (33)$$

$$\underline{P}_e^d \cdot ud_{et}^s \le Pd_{et}^s \le \bar{P}_e^d \cdot ud_{et}^s \quad (34)$$

$$En_{et}^s = \eta_e \cdot Pc_{et}^s - Pd_{et}^s \quad (35)$$

$$P_{et} = Pc_{et}^s + Pd_{et}^s \quad (36)$$

$$E_{e,t} = E_{e,t-1} - En_{e,t}^s \quad (37)$$

$$E_e^{\min} u_{et} \le E_{et}^s \le E_e^{\max} u_{et} \quad (38)$$

$$E_{e,0} = E_{e,24} \quad (39)$$

$$uc_{e,t}^s + ud_{e,t}^s \le u_{et} \quad (40)$$

Constraint (28) represent power balance at the stress condition, where wind deviations are counterweighed by deploying ramp-up/ down provided by thermal units, ES system and flexible demand, in addition to load curtailment.

The power output of thermal unit g during period t and stress condition s is described by (29), and the actual load for flexible demand d in period t and stress condition s by (30). The flexible ramping (FR) deployment provided by the conventional and fast-ramping thermal units shall respect the generation limits, and the FR deployment provided by the ES system and flexible demands must be within the energy storage and demand limits at stress condition. These limits are considered in (31) and (32), respectively. Where $\bar{\Delta}r_{gt}^{s} / \underline{\Delta}r_{gt}^{s}$ and $\bar{\Delta}r_{dt}^{s} / \underline{\Delta}r_{dt}^{s}$ represents physically acceptable adjustments of thermal units and flexible demand in ten minutes (i.e., 10/60 of hourly ramping of thermal units) to absorb the volatility of WEPs [18]. Constraints (33) and (34) provide ES system charge and discharge power. Net hourly charge and discharge energy and dispatched power of the ES system are presented in (35) and (36), which explain that the difference between the energy stored and injected (or discharge energy) back to the grid by the ES system is computed by the charging cycle efficiency. The hourly energy balance is given in (37). Constraint (38) shows the ES system capacity limits. Constraint (39) implies that the storage has a daily cycle when the state of charge at the last period (t=24h) is equal to that of the initial time (t=0h). Hourly ES system charge and discharge modes, which are mutually exclusive, are given by (40).

B. System Flexibility Metric

In this paper, a novel system flexibility metric model in a day-ahead scheduling problem is developed to address the uncertainties linked with WEPs. The proposed method is non-probabilistic and doesn't need any probability density function. Without loss of generality, the minimization process is presented hereafter:

$$\min_{X} f(X, \Psi) \tag{41}$$

$$H_i(X, \Psi) \le 0, \quad i \in \Gamma_{ineq} \tag{42}$$

$$G_j(X, \Psi) = 0, \quad j \in \Gamma_{eq} \tag{43}$$

$$\Psi \in U \tag{44}$$

where, Γ is the set of all equality and inequality constraints, Ψ is the uncertain input parameters set, and H/G are the set of inequalities/equalities for a decision variables set X . In addition, U represents the uncertainty set depicting the uncertain input parameters.

There are numerous model types for the uncertain parameters in accordance with their attributes. Thus, the envelope bound model is employed to denote previous information about uncertain input parameters Ψ, given by [22]:

$$\forall \Psi \in U(\bar{\Psi}, \alpha) = \left\{ \Psi : \left| \frac{\Psi - \bar{\Psi}}{\bar{\Psi}} \right| \le \alpha \right\} \tag{45}$$

where $\bar{\Psi}$ is the predicted value of the uncertain parameter, i.e., Ψ , and α is the unknown radius of uncertainty. The deterministic model of (41)–(44) optimizes the problem based on the forecasted value of the uncertain parameter.

The decision variables should be defined so that the worst case deviation of Ψ is fulfilled, i.e., the maximum value of unknown uncertainty radius α.

Hence, the unique system flexibility metric formulation is given by:

$$\text{Max } SFI \tag{46}$$

$$P_{wt}^{s} = (1 \pm \alpha_i) \cdot P_{wt}^{0}, \quad s = \pm, i = 1,2,...,n \tag{47}$$

$$TC \le (1 + \xi) \cdot TC_b \tag{48}$$

The objective function (46) of the above problem is to maximize the system flexibility index. The lower/upper wind uncertainty condition is specified by constraint (47), where, $s = \pm$, "$\pm$" in (47), "+" and "–" refer to the upper and lower boundaries of possible wind uncertainty, respectively.

The wind uncertainty level considered ranges from 0 to 1 in such a way that α uncertainty means that the *upper* and *lower* boundaries of possible wind uncertainty are equal to the wind power forecast multiplied by $(1+\alpha)$ and $(1-\alpha)$, respectively. To derive the day-ahead scheduling problem with wind uncertainty, we can attain the largest range of variation of wind uncertainty that the system can hold with flexible resources. Once the α_i is increased at each step by 0.01%, if the value of SFI becomes constant at a given step, say $i+1$, α_i is the largest wind uncertainty range that the system can endure within the response time, and the cost threshold is given by $(1+\xi)TC_b$.

Note: constraint (48) specifies that the cost of corrective actions should not surpass the cost threshold $(1+\xi)\cdot TC_b$ for any uncertainty outcome. The selection of the threshold for the cost depends on the conservatism level of the decision makers'. Moreover, the day-ahead problem is certainly feasible for $\xi = 0$. The ξ is a positive parameter set by the decision maker. It specifies the degree of acceptable tolerance on increasing (deteriorating) the value of base total energy cost due to the possible undesired uncertainties. The ξ in equation (48) indicates that the cost of the corrective actions must not exceed the cost threshold $(1+\xi)TC_b$ for any realization of uncertainty. The choice of cost threshold with ξ depends on decision makers' conservatism level. Compared to a risk-taker, a risk-averse decision maker would be willing to pay more in order to keep system remain reliable with respect to large disturbance, so his cost threshold would be higher. For all of the test systems, our proposed problem with (without) flexible resources is certainly feasible for ξ = 0. However, as the ξ parameter decreases, i.e. ξ < 0, our proposed problem may become infeasible because the equation (48) cannot be satisfied. Here, ξ is set to be zero to comparing system flexibility index for all cases. Overall, we can consider any value for ξ>0 to comparing system flexibility, no impact on the behavior of our results and analyze.

Here, we use the SFI, alpha and cost threshold in the proposed model as basis to construct an online flexibility metric. In particular, we first identify the largest variation range of uncertainty within which the system can remain feasible under given response time horizon and cost threshold. The flexibility metric is obtained by comparing the SFI with largest variation range with the target range to reflect the excessive availability of the system relative to the target variation range. The first step to measure flexibility or SFI is to clarify the cost threshold, and the target alpha variation range. The first two elements indicate the economic boundary, respectively.

TABLE I: THERMAL UNITS DATA AND TRANSMISSION LINE DATA; THE 6-BUS SYSTEM.

Units	Energy bid price ($/MWh)	Start up/ Shut down cost ($)	P^{max} (MW)	P^{min} (MW)	Min Up (h)	Min Down (h)	Ramp up/down rate (MW/h)
G1	20	100/0	220	100	4	4	55
G2	35	200/0	150	20	3	2	50
G3	50	50/0	50	10	1	1	40
FRU	50	40/0	50	10	1	1	100

TABLE II: STORAGE DATA; THE 6-BUS SYSTEM.

Capacity (MWh)	Max charge (MW)	Min charge (MW)	Max discharge (MW)	Min discharge (MW)
100	50	30	50	30

TABLE III TRANSMISSION LINE DATA; THE 6-BUS SYSTEM.

Line no.	From Bus	To Bus	X(p.u.)	Max. line flow (MW)
1	1	2	0.17	60
2	1	4	0.258	150
3	2	3	0.037	150
4	2	4	0.197	150
5	3	6	0.018	150
6	4	5	0.037	40
7	5	6	0.140	150

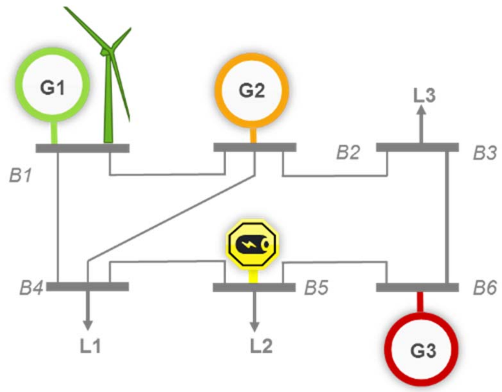

Fig. 3. One-line diagram for six-bus system.

The target alpha variation range serves as a basis for evaluating flexibility, reflecting decision makers' risk level.

Note: the alpha is a parameter and is prespecified by decision makers as input parameters that identified before runs optimization procedure. Also, the SIF is a variable and determines after runs optimization procedure based on alpha value.

V. CASE STUDY

A modified 6-bus and the IEEE 118-bus systems are considered to examine the proposed system flexibility metric in the day-ahead scheduling with flexible resources.

The proposed model has been formulated as a MILP problem, being solved in GAMS with the CPLEX solver on a 4.20 GHz CPU with 32 GB RAM.

A. *Modified six-bus system*

The 6-bus system illustrated in Fig. 3 has three thermal units, seven transmission lines, and three demands. The characteristics of thermal units and transmission lines are given in Tables I-III. The wind farm unit with a maximum power output of 140 MW is installed at bus 1, which is about 43% of the system peak load.

The cost of load curtailment is 500 $/MWh. The responsive demand bid consists of a single energy block with a bidding price of 45 $/MWh. The minimum up/down times are 2 h and the demand up/down rates are considered to be large enough to allow any demand changes in successive hours. All of the demands offer to sell 'ramping up/down at 20 $/MWh and the deployment cost of ramping up/down for each thermal unit is 15 $/MWh. The percentage of available wind farm unit and system load for each hour is given in Fig. 4. To study the influence of flexible resources available, FRU, hourly DR and ES system on system flexibility index (*SFI*), the following two cases are tested as follows:

-***Case* 1:** This case provides a reference in which the *SFI* and α value for a day-ahead scheduling problem are optimally found without flexible resources.

-***Case* 2:** The effect of FRU on Case 1 is investigated.

-***Case* 3:** The effect of hourly DR on Case 1 is investigated.

-***Case* 4:** The effect of the ES system on Case 1 is investigated.

-***Case* 5:** The co-operation effect of available flexible resources on Case 1 is investigated.

***Case* 1:** As it was already explained, the first step, the day-ahead scheduling problem, i.e., (14)-(27), without any FRs, has been solved to calculate the objective function of the base case, i.e., TC_b. It is assumed that the forecasted WEP is at 100% of the wind farm installed capacity at bus 1. The total cost of energy procurement is equal to $TC_b = 75742.256\,\$$, including thermal generation.

At the second stage, the day-ahead scheduling problem (41)-(42) without any FRs, has been solved to obtain the minimum *SFI* value (or minimum amount of flexibility required). For this test system minimum flexibility amount is 0.263.

The details of the minimum amount of flexibility required are described as follows:

1) the alpha value is fixed to zero, i.e., .
2) the "Max SIF" obtained for .

The SIF obtained is the minimum amount of flexibility required by a power system.

In this case, the day-ahead scheduling problem without FRs is certainly feasible for $\alpha = 0$. However, as the wind uncertainty parameter α increases, the day-ahead scheduling problem may become infeasible because the desired value of α cannot be reached. Nevertheless, since the wind uncertainty parameter is increased at each step by 0.1%, if the solution is infeasible at a specified step, say $i+1$, is the maximum wind uncertainty condition with an error lesser than 0.1%.

Simulations results are depicted in Table IV and V and Fig. 5. Note that the conservativeness parameter ξ is set to zero. As shown in Fig. 5, the *SFI* and α value without any FRs are 0.285 and 0.043, here, these obtained results are taken as a baseline for comparison.

TABLE IV
HOURLY UNIT COMMITMENT (UC) UNDER DIFFERENT FLEXIBLE RESOURCES

No. FRs	Units Always Online: G3
Unit	Hours (1-24)
G1	0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0
G2	0 0 0 1 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
FRU	**Unit Always Online: G2**
Unit	Hours (1-24)
G1	0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0
G3	0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
DR	**Unit Always Online: G2**
Unit	Hours (1-24)
G1	0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
G3	0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
ES	**Units Always Online: G3**
Unit	Hours (1-24)
G1	0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0
G2	0 0 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 0 0
FRU+DR+ES	**Unit Always Offline/Online: G1/G3**
Unit	Hours (1-24)
G2	0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0

TABLE V: FLEXIBILITY INDEX FOR THE AVAILABLE FLEXIBLE RESOURCES IN SIX-BUS SYSTEM

Name	Flexibility Index				
	No.FR	**FRU**	**DR**	**ES**	**FRU+DR+ES**
System Generation	0.285	0.396	0.339	0.309	0.576
System Demand	0.000	0.000	**0.857**	0.000	**0.673**
ES System	0.000	0.000	0.000	0.400	0.400

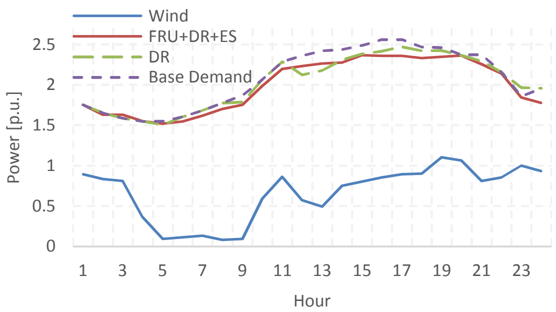

Fig.4. Comparison of WPG output and daily load profile.

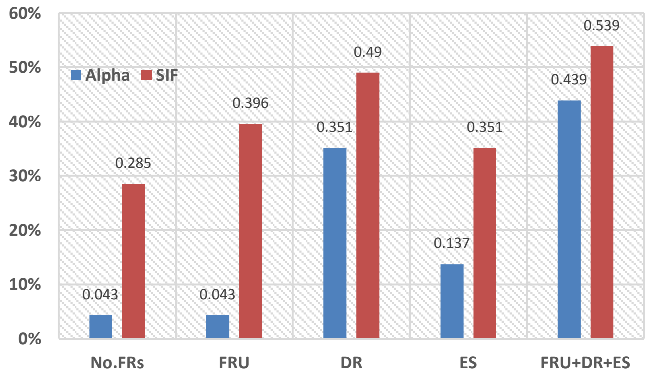

Fig.5. The *SFI* and α value under different available flexible resources in six-bus system.

In this condition, real-time generation of the wind farm is 146.02 MW which is 6.02 MW more than the expected value. This means that for $\alpha > 0.043$, the proposed problem (41)-(42) without any FRs becomes infeasible and wind uncertainty enters to the inadmissible region.

The unit commitment with a dc network security check is employed to determine the results given in Table IV. The cheaper and lower flexible unit G2 is on at most hours to satisfy the system load and minimize operation cost while unit G1 with higher flexibility (than unit G2) is used to satisfy remaining system load. Unit G3, with the highest flexibility, is committed at all hour due to satisfy system ramping up/down requirements in wind uncertainty condition. In addition, the transmission network faces flow violations on lines 1–4 and 4–5.

Thus, the most expensive (with the highest flexibility) unit G3 is activated at all hours assist in mitigating violations. Lines 4–5 are congested at peak hours 15–19, leading to lower dispatch of the wind farm and unit G1 and a higher operating cost, having as a result a lower SFI and α value.

***Case* 2-5:** In these cases, the effect of flexible resources available, FRU, hourly DR and ES system on the *SFI* and α value with a 100% of available wind energy are investigated. In the previous case, system congestion (due to lines 1–4 and 4–5 is the main hindrance to augment system's level of flexibility, i.e., the *SFI* and α value. In *Case* 1, if there were no FRs in the coordinated scheduling, the system would surpass in part this congestion by supply-side flexibility resource (commitment and dispatch of the thermal units). In order to decrease the power flow on these lines, two main options can be used: reducing the share of WEP (or reduce α value) to supply system load and/or implement existing FRs. Reducing the share of the WEP at bus 1 would imply a reduction in the power flow of the congested lines 1–4 and 4–5. Since decreasing the WEP share in supplying the load is considered to be an expensive option, using the flexible resources could be a more economical choice. By analyzing the FRU, hourly DR and ES system as FRs and the corresponding results in Fig. 5., we can better know the effect of each FRs on system flexibility, *SFI* and the maximum radius of the WEP uncertainty, the α value.

In ***Case* 2**, the effect of the FRU on the *SFI* and α value is analyzing, for this reason, unit G3 in Case 1 replacement with an FRU which is a quick-start and fast-ramping unit with a 50-MW and 50-MW/(10min) capacity, respectively. Second, comparing scheduling system results for the FRU (or *Case* 2) with *Case* 1, the *SFI* in scheduling system with FRU is increased from 28.5% to 39.6%, whereas the α

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value, as well as the wind energy utilization, remain nearly the same. As the up/down ramping for FRU (new G3 unit) is much more flexible than that of unit G3 in Case 1, the FRU carried out more ramping up/down and dispatched less, for this reason, here, the *SFI* is more increased than the same index in *Case* 1. Nevertheless, the congestion at line 1–4 is the main obstacle to increase α value which is caused wind farm unit (at bus 1) will not be able to increase output. Also, power dispatch and commitment of the FRU cannot overcome this transmission congestion. In this condition, the new UC is basically the same as in *Case* 1, but unit G2 is committed at hours 5–7. In Fig. 5, the *SFI* and α value for hourly DR (for *Case* 3) is 0.490 (or 49.0%) and 0.351 (or 35.1%), respectively. It means that if *SFI* increases up to 49.0%, then a WEP uncertainty (α value) of 35.1% is insured. The congestion in lines 1–4 and 4–5 implies that α value could not be increased. In Case 3, to decrease the power flow on these lines (higher α value), three main solutions are typically used: reduce the share of WEP, and/or increase the output of thermal unit G3, and/or hourly DR. Hourly DR by decreasing the load at buses 4 and 5 could imply a decrease in the flow of lines 1–4 and 4–5. Likewise, a higher power dispatch of thermal unit G3 at bus 6 and a reduction in the share of the WEP at bus 1 could imply a reduction in the flow of congested lines 1-4 and 4–5. Since the power dispatch of thermal unit G3 and the reductions of the share of the WEP are assumed to be an expensive option in *Case* 3, hourly DR is the economical choice. In addition, by comparing *Case* 1 and *Case* 3, the hourly DR in Fig. 5, the *SFI* and α value are increased by 87.7% and 41.1%, respectively.

In ***Case* 3**, as shown in Fig. 5 and Table IV, the wind uncertainty is compensated by the hourly DR and thermal unit G2, (for this reason this unit is always online).

As shown in Fig. 4, the hourly DR in *Case* 3 causes load profile at peak hours is decreased. Accordingly, comparing between hourly DR and FRU, the hourly DR is the best option to increase α value.

Moreover, if the ES system could join the system, in ***Case* 4**, the system could surpass the system congestion (caused by line 4–5, having the lowest capacity) by managing ES system's charging/discharging performance (the ES flexibility resource). For instance, in *Case* 1, lines 1–4 and 4–5 are congested at peak hours 15–19, which implies a lower dispatch of units G1 and G2 and an inferior WEP uncertainty α value (as shown in Fig 5). In this case, the ES system at peak hours 15–19, by its charging behavior absorbing power injection to bus 5, may decrease power flow in line 4–5 and increase power flow in lines 1–4 and 5-6 to counterweigh the deficit in contributing to the demand located at buses 4 and 5. Thus, the ES system will cause a similar schedule as in *Case* 1, but the dispatch of units G1 and G2 is augmented by reducing power flow of line 4–5.

To study the cooperation of FRU, hourly DR and ES, all of them have been concurrently considered in ***Case* 5**. Indeed, the shortcomings of previous cases are improved by this cooperation of all these flexible resources at the same time. For instance, co-operation of hourly DR and ES system by managing of hourly system energy consumption can relieve system congestion and augment the FRU efficiency. Hourly DR and ES system at buses 4 and 5 would imply a flow decrease in Lines 1-4 and 4-5. For this reason, as can be seen in Table IV, the commitment of FRU is increased from 21 hours in *Case* 2, to 24 hours in *Case* 4, due to a reduction in the flow of congested lines 1-4 and 4-5. In addition, numerical results in Fig. 4 and 5 for *Case* 5 demonstrate that hourly DR with co-operation of the FRU and ES system offers a flat load profile at peak hours that leads to lesser congestions, lower the *SFI* and α value. For this reason, comparing *Cases* 1 and 4 in Fig. 5, the *SFI* and α value are increased by 47.12% and 90.2%, respectively. It means in comparison with *Cases* 2-3 these variables are more increased in *Case* 4. Fig. 5 provides the flexibility indices computed for the supply side, demand side and storage side flexibility and for the whole test system by means of the method given in Section II. Comparing the flexibility index of a particular flexible resource with the flexibility index for the whole system, it is possible to evaluate the contribution to the flexibility of the overall system. If its index is higher than the system's flexibility index, this FR has more effect on the flexibility of the overall system. For example, in *Case* 5, the hourly DR has a flexibility index of 0.673. In this case, the hourly DR have more effect on total system flexibility, while the ES system with the lowest flexibility index has a lower effect on system flexibility. These flexibility indices, in Table V, are joined to make FR mixes with separate flexibility index levels that are considered in our studies. For instance, a highly flexible mix is comprised of three resources of FRU, hourly DR and ES system. The same standard is used to generate the low and medium flexibility mixes. Table V provides the composition of each mix regarding the aggregated flexibility index of FRs. A high flexibility mix (index 0.539) is capable of mitigating 43.9% of wind uncertainty, which is a substantially larger fraction than the other two groups. The low flexibility mix (index 0.285) is only capable of accommodating 4.3% of the wind uncertainty, which implies that 39.6% of WEP needs to be curtailed as a consequence of flexibility constraints.

B. Modified IEEE 118-Bus Large-Scale System

The modified IEEE-118 bus system has 54 thermal units, 186 branches, and 91 load buses. The generators, transmission network and load profiles parameters are provided in [19].

There are four geographically dispersed WEP including four wind turbines (at Buses 15, 24, 54 and 96). The wind energy generation capacity is 2250 MW. The wind output profile of the WPG units pursues the same pattern as that of the six-bus system. System peak demand corresponds to 6000 MW at hour 21. The installed WEP is 37.5% of the system peak load. Four ES systems with a capacity of 100 MWh are installed at buses with WEP. The five cases, which were addressed in the previous system, are also inspected for this system.

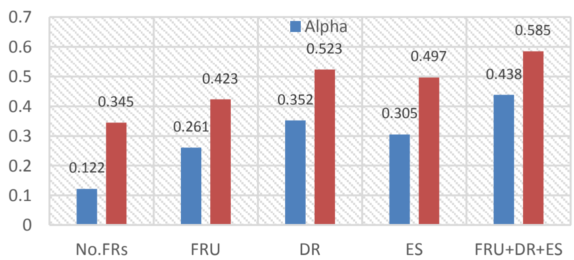

Fig.6. The *SFI* and α value under different available flexible resources in modified IEEE 118-bus system.

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Fig 6 shows the *SFI* and α value in different cases. The results in this figure are in line with those of the previous system. *SFI* and α value have the lowest and highest values in *Case* 1 and *Case* 5, respectively. In addition, the FRU, hourly DR and ES system would be effective tools to compensate the uncertainty of WEP in the large system.

However, by adding flexible options (e.g., FRU, hourly DR and ES system) to the system, the *SFI* and α value are increased. For example, compared to *Case* 1, the α value in *Case* 3 is increased by incorporating hourly DR program. In comparison with the commitment of FRU (or *Case* 2), the hourly DR is an improved option amongst flexible resources since it frequently yields more flat load profiles and lower system congestion. Accordingly, the α value in *Case* 3 and 5 is more increased as compared to *Cases* 1, 2 and 4. It can be inferred that when the FRU, hourly DR and ES system (*Case* 5) are taken into account, the system would have the highest wind uncertainty absorption capacity. Higher WEP uncertainty (or higher α value) results in further power system fluctuations and would need higher up/down ramping requirements and additional flexibility in power system operations. For this reason, the *SFI* in *Case* 5 has the highest value.

VI. Conclusion

Flexibility is becoming an important concept in academic studies and industry reports lately, although a combined framework for assessing power system flexibility is still missing. Hence, this paper presented a novel online system for unified flexibility formulation of a day-ahead scheduling model including various types of flexible resources (thermal units, demand and energy storage), which can soundly be modeled using mixed integer linear programming (MILP). Compared to previous works, the proposed flexibility metrics clearly took into account the impacts of flexible resources, which play a crucial task in system flexibility. In addition, numerical results confirmed that with improved system flexibility, the *SFI* and α value increased. In addition, it was shown that the highest system flexibility with the largest *SFI* and α value would be obtained by combining FRU, hourly DR and ES. Furthermore, the results indicated that hourly DR could play a very important role in system flexibility.

VII. References

[1] U.S. NREL, 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply [Online]. Available: http://www.nrel.gov/docs/fy08osti/41869.pdf.

[2] A. Nikoobakht, M. Mardaneh, J. Aghaei, V. Guerrero-Mestre, and J. Contreras, "Flexible power system operation accommodating uncertain wind power generation using transmission topology control: an improved linearised AC SCUC model," *IET Generation, Transmission & Distribution,* 2016.

[3] B. F. Hobbs, J. C. Honious, and J. Bluestein, "What's flexibility worth? The enticing case of natural gas cofiring," *The Electricity Journal,* vol. 5, pp. 37-47, 1992.

[4] A. Nikoobakht, J. Aghaei, and M. Mardaneh, "Managing the risk of uncertain wind power generation in flexible power systems using information gap decision theory," *Energy,* vol. 114, pp. 846-861, 2016.

[5] A. Nikoobakht and J. Aghaei, "IGDT-Based Robust Optimal Utilization of Wind Power Generation Using Coordinated Flexibility Resources," *IET Renewable Power Generation,* p. 60 pp, 2016.

[6] J. Zhao, T. Zheng, and E. Litvinov, "A unified framework for defining and measuring flexibility in power system," *IEEE Transactions on Power Systems,* vol. 31, pp. 339-347, 2016.

[7] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems," in *IEEE PES GM 2013*, 2013, pp. 1-11.

[8] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of power system flexibility," *IEEE Transactions on Power Systems,* vol. 27, pp. 922-931, 2012.

[9] H. Nosair and F. Bouffard, "Flexibility envelopes for power system operational planning," *IEEE Transactions on Sustainable Energy,* vol. 6, pp. 800-809, 2015.

[10] S. Nabavi, M. Masoum, and A. Kazemi, "An Optimal Transmission Congestion Management in Open Power Markets," *Int. Review of Automatic Control,* vol. 3, pp. 424-431, 2010.

[11] S. Nabavi, A. Kazemi, and M. Masoum, "Congestion management using genetic algorithm in deregulated power environments," *Int. Journal of Computer Applications,* vol. 18, pp. 19-23, 2011.

[12] F. Li and J. Pan, "Assessment of quick start resource requirements in market operations," in *Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES*, 2006, pp. 1363-1367.

[13] H. Wu, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Thermal generation flexibility with ramping costs and hourly demand response in stochastic security-constrained scheduling of variable energy sources," *Power Systems, IEEE Transactions on,* vol. 30, pp. 2955-2964, 2015.

[14] V. Hamidi and F. Li, "Value of windfarm location and penetration on operation of power system and benefits of responsive demand," in *Electric Utility Deregulation and Restructuring and Power Technologies Conference*, 2008, pp. 2712-2718.

[15] F. Abbaspourtorbati, A. J. Conejo, J. Wang, and R. Cherkaoui, "Is Being Flexible Advantageous for Demands?," *IEEE Transactions on Power Systems,* vol. 32, pp. 2337-2345, 2017.

[16] N. G. Paterakis, O. Erdinc, A. G. Bakirtzis, and J. P. Catalão, "Load-Following Reserves Procurement Considering Flexible Demand-Side Resources Under High Wind Power Penetration," *Power Systems, IEEE Transactions on,* vol. 30, pp. 1337-1350, 2015.

[17] P. Siano, "Demand response and smart grids—A survey," *Renewable and Sustainable Energy Reviews,* vol. 30, pp. 461-478, 2014.

[18] H. Cui, F. Li, Q. Hu, L. Bai, and X. Fang, "Day-ahead coordinated operation of utility-scale electricity and natural gas networks considering demand response based virtual power plants," *Applied Energy,* vol. 176, pp. 183-195, 2016.

[19] A. Yunus, Y. Alharbi, A. Abu-Siada, and M. S. Masoum, "Overview of storage energy systems for renewable energy system application," in *Proceeding of 3rd Makassar International Conference on Electrical Engineering and Informatics*, 2012.

[20] M. Parvania, M. Fotuhi-Firuzabad, and M. Shahidehpour, "ISO's Optimal Strategies for Scheduling the Hourly Demand Response in Day-Ahead Markets," *Power Systems, IEEE Transactions on,* vol. 29, pp. 2636-2645, 2014.

[21] M. Alizadeh, M. P. Moghaddam, N. Amjady, P. Siano, and M. Sheikh-El-Eslami, "Flexibility in future power systems with high renewable penetration: A review," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 1186-1193, 2016.

[22] L. F. Wright, "Information Gap Decision Theory: Decisions under Severe Uncertainty," *Journal of the Royal Statistical Society: Series A (Statistics in Society),* vol. 167, pp. 185-186, 2004.

Ahmad Nikoobakht was born in Iran in 1988. He received the B.Sc. degree in electrical engineering from Hormozgan University, Iran, in 2011, and the M.Sc. and Ph.D. degrees from Shiraz University of Technology, Shiraz, Iran, in 2013 and 2017, respectively. He is currently an Assistance Professor in the Electrical Engineering Department of Higher Education Center of Eghlid, Eghlid, Iran. His research interests include renewable energy systems, smart grids, electricity markets, and power system operation and restructuring, as well as statistics and optimization theory and its applications.

Jamshid Aghaei (M'12-SM'15) received the B.Sc. degree in electrical engineering from the Power and Water Institute of Technology, Tehran, Iran, in 2003, and the M.Sc. and Ph.D. degrees from the Iran University of Science and Technology, Tehran, in 2005 and 2009, respectively. He is currently an Associate Professor at the Shiraz University of Technology, Shiraz, Iran, and also a Research Fellow at the Norwegian University of Science and Technology, Trondheim, Norway. His research interests include renewable energy systems, smart grids, electricity markets, and power system operation, optimization, and planning. Dr. Aghaei is a Member of the Iranian Association of Electrical and Electronic Engineers, an Associate Editor of the *IET Renewable Power Generation* and a Guest Editor of the IEEE Transactions on Industrial Informatics. He was considered one of the outstanding reviewers of the IEEE Transactions on Sustainable Energy in 2017.

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Miadreza Shafie-khah (M'13-SM'17) received the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2008 and 2012, respectively. He received his first postdoc from the University of Beira Interior (UBI), Covilha, Portugal in 2015, while working on the 5.2-million-euro FP7 project SiNGULAR ("Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration"). He received his second postdoc from the University of Salerno, Salerno, Italy in 2016. He is currently an Assistant Professor eq. and Senior Researcher at CMAST/UBI, where he has a major role of coordinating a WP in the 2.1-million-euro national project ESGRIDS ("Enhancing Smart GRIDS for Sustainability"), while co-supervising four PhD students and two post-doctoral fellows. He was considered one of the Outstanding Reviewers of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, in 2014 and 2017, one of the Best Reviewers of the IEEE TRANSACTIONS ON SMART GRID, in 2016 and 2017, and one of the Outstanding Reviewers of the IEEE TRANSACTIONS ON POWER SYSTEMS, in 2017. His research interests include power market simulation, market power monitoring, power system optimization, demand response, electric vehicles, price forecasting and smart grids.

João P. S. Catalão (M'04-SM'12) received the M.Sc. degree from the Instituto Superior Técnico (IST), Lisbon, Portugal, in 2003, and the Ph.D. degree and Habilitation for Full Professor ("Agregação") from the University of Beira Interior (UBI), Covilha, Portugal, in 2007 and 2013, respectively.

Currently, he is a Professor at the Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal, and Researcher at INESC TEC, INESC-ID/IST-UL, and C-MAST/UBI. He was the Primary Coordinator of the EU-funded FP7 project SiNGULAR ("Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration"), a 5.2-million-euro project involving 11 industry partners. He has authored or coauthored more than 625 publications, including 225 journal papers (more than 65 IEEE Transactions/Journal papers), 350 conference proceedings papers, 2 books, 34 book chapters, and 14 technical reports, with an h-index of 38, an i10-index of 145, and over 5950 citations (according to Google Scholar), having supervised more than 50 post-docs, Ph.D. and M.Sc. students. He is the Editor of the books entitled Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling and Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids (Boca Raton, FL, USA: CRC Press, 2012 and 2015, respectively). His research interests include power system operations and planning, hydro and thermal scheduling, wind and price forecasting, distributed renewable generation, demand response and smart grids.

Prof. Catalão is an Editor of the IEEE TRANSACTIONS ON SMART GRID, an Editor of the IEEE TRANSACTIONS ON POWER SYSTEMS, and a Subject Editor of the *IET Renewable Power Generation*. From 2011 till 2018 (seven years) he was an Editor of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY and an Associate Editor of the *IET Renewable Power Generation*. He was the Guest Editor-in-Chief for the Special Section on "Real-Time Demand Response" of the IEEE TRANSACTIONS ON SMART GRID, published in December 2012, and the Guest Editor-in-Chief for the Special Section on "Reserve and Flexibility for Handling Variability and Uncertainty of Renewable Generation" of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, published in April 2016. Since May 2017, he is the Corresponding Guest Editor for the Special Section on "Industrial and Commercial Demand Response" of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS. Since March 2018, he is the Lead Guest Editor for the Special Issue on "Demand Side Management and Market Design for Renewable Energy Support and Integration" of the *IET Renewable Power Generation*. He was the recipient of the 2011 Scientific Merit Award UBI-FE/Santander Universities, the 2012 Scientific Award UTL/Santander Totta, the 2016 FEUP Diploma of Scientific Recognition, and the Best INESC-ID Researcher 2017 Award, in addition to an Honorable Mention in the 2017 Scientific Awards ULisboa/Santander Universities. Moreover, he has won 4 Best Paper Awards at IEEE Conferences.