

POWER SYSTEM FLEXIBILITY METRICS REVIEW WITH HIGH PENETRATION OF VARIABLE RENEWABLE GENERATION

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Abstract:

Power systems face growing flexibility requirements for managing the increased penetrations from variable renewable generation, VRG, like solar and wind power generation. In general, instant balance of temporal inequalities between supply and demand can be reached by many flexibility options. However, an accurate quantification of the flexibility needed and available in a power system is a complex task. Accordingly, this paper introduces a review of various power system flexibility metrics that used to quantify the flexibility. The use of these metrics varied, some of them were used to measure the flexibility available from each conventional generator and others were used to measure the flexibility available and needed by the power system at either the planning and operational stages but up - till - now there is no flexibility metric that can be taken as a standard.

Keywords:

Power system flexibility, variable generation (VG), renewable energy.

ACM Computing Classification System:

Power estimation and optimisation, interconnect power issues, renewable energy.

1 Introduction

The continuous growth of VRG penetration has led to draw attention that future power systems may have not enough flexibility to deal with power ramps in both VRG and system demand. Due to the variability and uncertainty of their output. The power system flexibility is the power system capability to deploy its power resources to respond to net load changes, as net load is the system demand minus VG output [1] [2]. A review of different flexibility definitions have been summarized in (Table.1).

At low penetration of renewable energy the requested flexibility has provided by the reserve generation and generators scheduling. As the system demand can be predicted to a large extent, short duration load changes can be met by regulation and load following power plants, whereas the contingency reserve are used for unpredicted outage of transmission line or generator. Hence with increased penetration of VRG, it is necessary to do a new evaluation of the reserve required, and how to measure or estimate the available and required flexibility in a power system. Although adequacy of generation can be simply determined, the calculation of system flexibility is more complicated and more detailed data will be required when compared to the adequacy calculations.

This paper reviews the different approaches of flexibility metrics studies. In which diverse flexibility metrics were developed to assess power system flexibility in operation or planning stages and to quantify the needed or available system flexibility.

Table 1. List of Flexibility Definitions

Flexibility Definitions	
1	The power system flexibility is the power system capability to deploy its power resources to respond to net load changes, as net load is the system demand minus VG output [1][2].
2	Flexibility is the capability of a power system to balance the rapidly variation in the output of renewable generation and forecast errors [3].
3	System flexibility is the aggregated system generators ability in responding to the net load variation and uncertainty [4].
4	Flexibility is the capability of controllable power components in producing or absorbing power at various rates, over diverse time scales, and under a variety of power system conditions [5].
5	The transmission system ability to maintain a desired level of reliability at acceptable operation costs even with changes in generation scenarios [6].
6	Flexibility is adaptation of the injected and/or consumed generation in response to an external signal such as price signal so as to provide a service within the power system. The parameters that used in characterizing flexibility consist of the amount of power that can be modulated, the duration, the rate of change, the location etc. [7].
7	The power system ability for responding to changes in electricity in both supply and demand [8].
8	System flexibility describes its ability for accommodating the increasing performance levels at insignificant extra expense for any timescale [9].
9	Flexibility is the capability of the system to react to a variety of unclear future conditions by going in an elective direction inside satisfactory cost limit and time window [10].
10	A power system is flexible if it can inside limits reacts quickly to vast changes in demand and supply, both scheduled and unexpected fluctuations and events, sloping down generation once demand decreases, and upwards once it increases [11].
11	A resource's ability, regardless it is a component or collection of power system components, to react to the known and unknown changes in power system conditions at different operational stages [12].
12	Flexibility refers to the ability of the system to manage events which may cause unbalance between electricity production and demand whereas ensuring system reliability in a financially savvy way [13].
13	In its vastest sense, system flexibility refers to the degree to which a power system can adapt to the patterns of electricity production and demand so as to keep up the balance between them within acceptable cost. While in a narrower sense, it refers to the degree to which generation or demand can be increased or decreased over a timescale extending from minutes to hours because of changeability, expected or otherwise [14].
14	Flexibility is typically characterized as the likelihood of altering production and/or demand patterns in response to an external signal such as price or activation signals in order to contribute cost-effectively to the stability of the power system [15][16].
15	The California ISO proposes flexibility in terms of rapid ramping capacity (to be delivered in 5 minutes) provided only from the supply side of the transmission grid, complementing the other regulatory services [17].
16	The concept of flexibility is generalized as "The capability of a power system to adjust the variation and uncertainty through economic deployment of available resources for a given time interval. From a probabilistic perspective, flexibility indicates the probability that the supply of flexibility is abundant compared to the demand during the period of concern." [18].

Specialized Definitions of Flexibility	
17	Economic flexibility is defined as “The ability to adapt, at a small extra cost, a wide range of possible short- term demand conditions.” [19].
18	A flexible plan is defined as “One that allows the utility to change the configuration or operation of the system rapidly and economically in response to different market and regulatory conditions.”[20].
19	Flexibility of the System is basically a <i>trackability</i> measure, the capability of the aggregate resources response to track any realization of the net load random process across the operating horizon [21] [22].
20	Operational flexibility is a power system’s ability to contain a disturbance fast enough to keep the power system secure. The most frequent disturbances are outage of components, such as transmission line or generator tripping, or power injection deviation, e.g., because of prediction errors [23] [24].
21	Locational flexibility is the operational flexibility accessible in the grid on a given bus. Which describes the disturbance that could be contained by appropriate and available remedial actions at a given system node [23].
22	The exportable flexibility is the operational flexibility in a local control area that can be utilized by neighboring control areas. Essentially, exportable flexibility is the amount of energy reserves that can be transmitted over the tie-lines between two adjacent areas [24].

2 Power Systems Need Flexibility

Introducing a large amount of VRG to power systems causes a lot of changes in load profile and balancing between electricity generation and consumption. Which in contrast to the conventional dispatchable power plants and there should be enough flexibility in the power system due to:

- a) VRG is dictated by climate conditions, so it is unsure ahead of time and there are forecast errors so specific power output is unclear until it is realized.
- b) VRGs are related to specific locations depending on the existence of sustainable sources of energy e.g., wind speed and solar irradiation, which are not associated with load centers.
- c) Expansion in the establishment of VRG plants displaces dispatchable conventional generation that adjusts its output to market conditions.
- d) The components failures that may happen to any of power system elements (generator, transmission line, transformer, etc.).

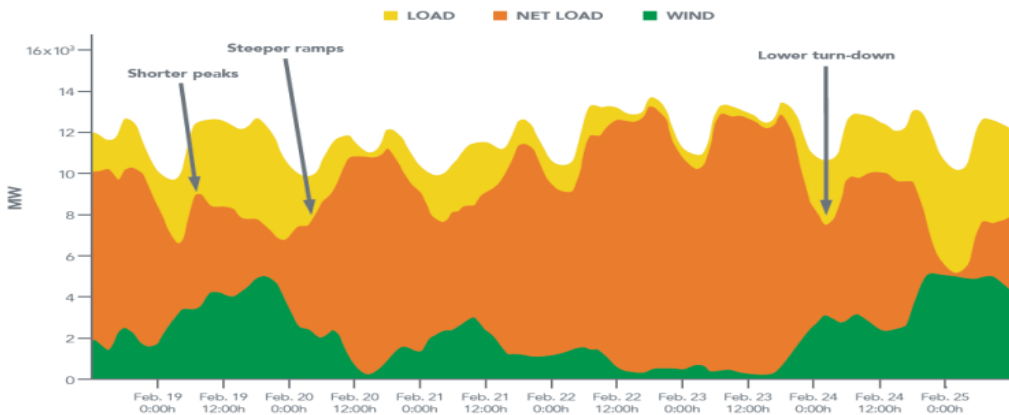


Fig.1. The effect of wind power production in net load.

(Fig.1) shows the effect of wind power generation in net load which can cause the following effects:

- i. Steeper ramps (Ramp is the rate of increment or reduction in dispatchable power generation or demand) if the wind power decreased at the same time that demand increased.
- ii. Shorter peaks periods in which conventional power generations operate fewer hours which affecting the cost.
- iii. Throughout the periods of low demand, higher wind production produces the need for dispatchable generators that can turn their output power down to the low levels but remain available to rapidly increase it again [25].

3 Inflexibility Impacts Power Systems

Sometimes, the explanation of the opposite meaning of a word leads to better understanding its meaning. So, features of inflexibility probably easier to be documented than flexibility. Examples of inflexibility in power system include:

- a) Difficult balance between demand and generation, leading to deviation of frequency or drop of loads.
- b) Curtailments of VRG, which occur when power generation is not required regularly (e.g., at night, seasonally), mostly happen because of abundance supply and when there are transmission limitations.
- c) Some Areas that have balance violations such deviations indicate how often a power system cannot fulfil its responsibility for balancing supply.

Examples of inflexibility in the wholesale markets of power:

- a) The negative prices that indicate many forms of inflexibility which include conventional power generation which could not decrease their output, load demand which unable to utilize the surplus power generation, excess of the renewable generation, and constrained transmission lines ability for balancing generation and demand and to transfer power over more extensive geographic areas. Nevertheless, negative prices sometimes happen without renewable generation in systems but it significantly increases with increasing penetration of renewable generation.
- b) Instability in prices, make prices swing between low and high, which can be a sign of restricted capacity of transmission lines, inadequate ramping availability, quick response, and peak power plants, and restricted demand side response [25].

4 Flexibility and Generation Adequacy

It is important to know the difference between power system flexibility and generation adequacy, generation adequacy metrics such as well-being analysis [26] [27] [28], loss of load expectation (LOLE) [29] [30], the expected energy not served (EENS), where power system flexibility was introduced to complement the traditional capacity adequacy for the power system. The difference between the two concepts is illustrated in (Table 2) [31].

Table 2. The difference between flexibility and generation adequacy

Generation Adequacy	System Flexibility
System demand profile used for adequacy calculations is relatively predictable.	High uncertainty degree surrounds the requirements for flexibility.
Generation Adequacy is a function of: <ul style="list-style-type: none"> a) Aggregated generators’s capacity available in the system. b) The forced outage rate of each resource. c) Yearly peak load hours. 	Flexibility of the system affected by several other issues: <ul style="list-style-type: none"> a) The generating resources in the system. b) The availability of each resource and its ramp rate. c) The frequency of net load ramps, magnitude and duration. d) Prediction of variations in net load. e) The interconnection between alternative systems. f) The existence of storage energy systems. g) Demand side response, DSR, availability. h) The arrangements of market in place. i) The strategies of reserve provision. j) Flexibility requirements varies according to the studied time horizon. k) Flexibility resources also depend on the time horizon to be studied.
Generation resources used only to provide capacity adequacy.	Generation resources used to provide both capacity adequacy and system flexibility.

5 Flexibility Metrics and Assessment Methods

Flexibility metrics have been developed by those concerned with real-time operations and the others interested in long-term planning. However, it is a complex task to accurately quantify the flexibility requirements for a VRG-based power systems. Flexibility metrics were utilized for the following objectives:

1. Metrics measure the system’s flexibility requirements.
2. Metrics measure the resource flexibility available.
3. Metrics measure the flexibility of the overall system including operation constraints and transmission lines constraints.

In [10] [32], the authors identified four elements as the determinants of flexibility which are time, uncertainty, action and cost. Flexibility was measured for power system planning as large variation range in the uncertainty within which the power system remains feasible under a certain time of response and cost threshold divided by the target uncertainty range the system intended to accommodate which depended on decision makers’ risk preference with taking into consideration transmission line network and constraints of system operation.

$$\text{flexibility} = \frac{\textit{the largest variation range of uncertainty the system can accommodate}}{\textit{the target variation range of uncertainty the system aim to accommodate}} \tag{1}$$

The power system operational flexibility was quantified and visualized in [33]. Where four parameters were used: power capacity (π), ramp-rate (ρ), energy capacity (ϵ) and duration of the ramp (δ).

Operational flexibility was described as the set-points of all possible operations that constrained by the three parameters ρ_{max}^{\pm} , π_{max}^{\pm} and ϵ_{max}^{\pm} , the signs of +/- denoted for power upward and downward. The relations between the individual parameters exhibit the dynamics of the so-called double integrator where, the integration of ramp-rate ρ (MW/min) gives the energy capacity ϵ (MWh), which is the integration of power capacity π (MW). For a power system unit (i), the three parameters span the flexibility cube, see (Fig.2).

Where, ρ_{max}^+ , ρ_{max}^- , π_{max}^+ , π_{max}^- , ϵ_{max}^+ and ϵ_{max}^- shaped the edges of the cube.

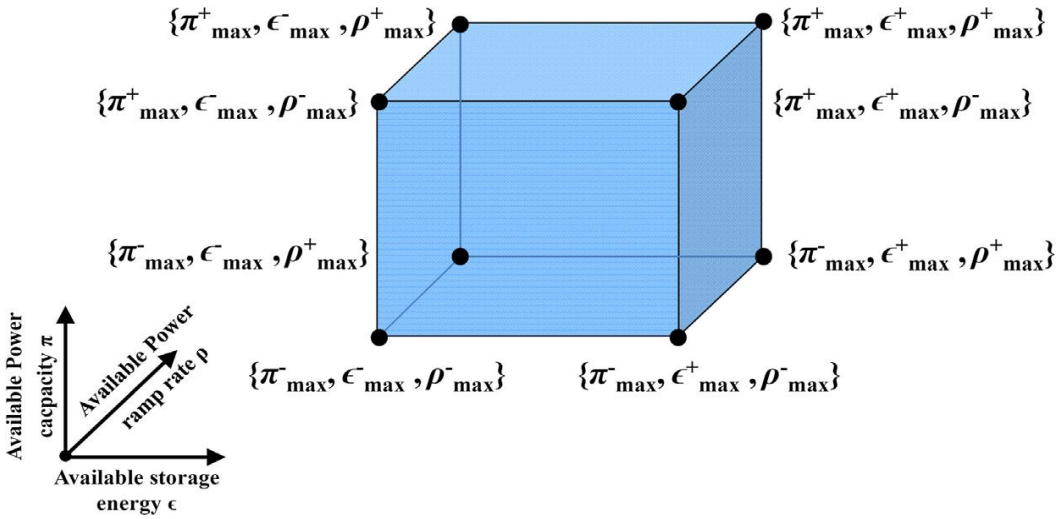


Fig.2. The cube of flexibility of a generic power system unit with maximum available operational flexibility.

According to the authors, aggregating different units in a power system result in increasing flexibility capability of the sum because their individual parameters of flexibility are added. For example, a slow dynamic unit like thermal or hydro power plant which characterized by low ρ , high π and ϵ constrained by fuel provision is operated with a highly dynamic unit of energy storage like a fly-wheel that characterized by high ρ , low π and limited or small ϵ , see (Fig.3).

$$\{\rho, \pi, \epsilon\}_{agg} = \{\rho, \pi, \epsilon\}_{slow} + \{\rho, \pi, \epsilon\}_{fast} \quad (2)$$

The overall operational flexibility provided by a pool of different units obtained by the summation of their flexibility volumes, i.e. the addition of their flexibility parameters.

$$\rho_{agg}^+ = \sum_i \rho_i^+ \quad , \quad \rho_{agg}^- = \sum_i \rho_i^- \quad (3)$$

$$\pi_{agg}^+ = \sum_i \pi_i^+ , \pi_{agg}^- = \sum_i \pi_i^-$$

$$\epsilon_{agg}^+ = \sum_i \epsilon_i^+ , \epsilon_{agg}^- = \sum_i \epsilon_i^-$$

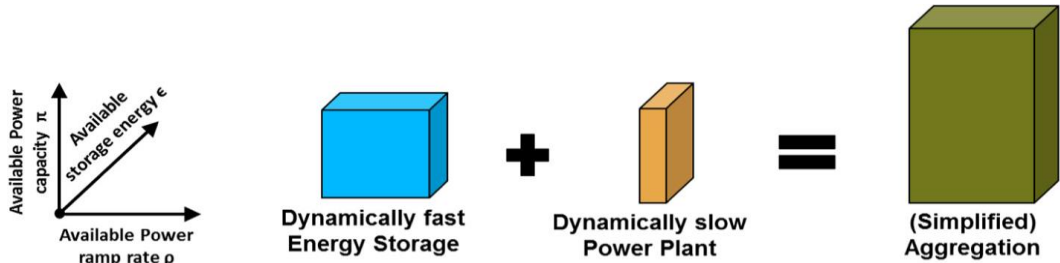


Fig.3. Collecting flexibility through power system units pooling.

In operation, the available flexibility in any power system should be at any case as that needed to mitigate an expected worst-case disturbance, see (Fig.4a). This condition is not only for the average but also for every time-step. The previous condition was illustrated by using figures, when the required flexibility cube fitted well into the available flexibility cube as in (Fig.4b). For power system accommodation to events that cause disturbance, the volume of the flexibility available should envelope the volume of the required flexibility. If not, there is at least one of the flexibility parameters axes lacking flexibility and the power system could not completely accommodate the disturbance events. Mathematically, the next conditions should be verified:

$$\rho_{needed}^+ \leq \rho_{available}^+ , \quad \rho_{needed}^- \leq \rho_{available}^-$$

$$\pi_{needed}^+ \leq \pi_{available}^+ , \quad \pi_{needed}^- \leq \pi_{available}^- \quad (4)$$

$$\epsilon_{needed}^+ \leq \epsilon_{available}^+ , \quad \epsilon_{needed}^- \leq \epsilon_{available}^-$$

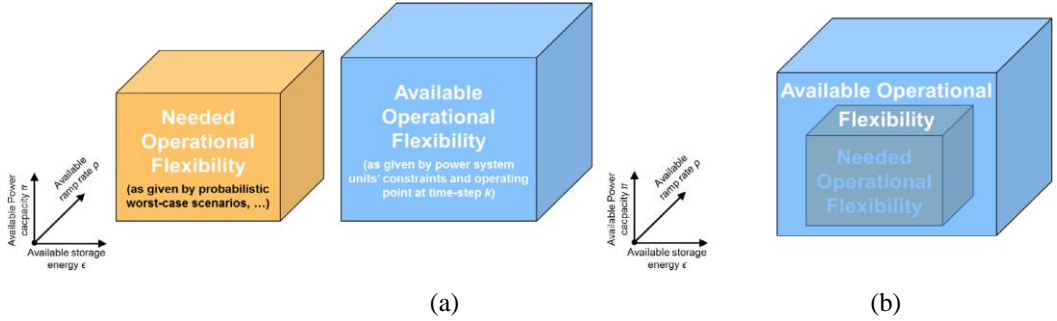


Fig.4. The flexibility needed versus that available during operation.

(a) Comparison. (b) The required condition for robust operation of the power system.

The authors in [34] proposed two “offline” indexes, the first offline index called normalized flexibility index, NFI, used in evaluation the capability of individual generating units and the ability of a mixture of generating units in providing the requested flexibility. The contribution of a generation unit to the generation mix's flexibility was determined by comparison its flexibility index to the entire system's flexibility index. The flexibility index of the individual generator (i) was given by:

$$flex(i) = \frac{\frac{1}{2}[P_{max}(i) - P_{min}(i)] + \frac{1}{2}[Ramp(i) \cdot \Delta t]}{P_{max}(i)}, \forall i \in A \quad (5)$$

Where, $flex(i)$ is positive and less than one, $P_{min}(i)$, $P_{max}(i)$ referred to minimum and maximum power output from generator i and average value's ramp up and down denoted by $1/2 Ramp(i)$.

The flexibility index of the entire system ($FLEX_A$) was then determined as the sum of the individual generator flexibility indices ($flex(i)$) multiplied by a weighting factor. The weighting factor was taken as each individual generator's capacity contribution. Therefore the flexibility of the entire system was calculated by the following equation:

$$FLEX_A = \sum_{i \in A} \left[\frac{P_{max}(i)}{\sum_{i \in A} P_{max}(i)} \times flex(i) \right], \forall i \in A \quad (6)$$

If the flexibility index of a certain resource was greater than that of the entire system, this resource in this system was classified as flexible. While, those power resources which were had a flexibility index lesser than the flexibility index of the system were inflexible resources. This classification of thermal generation units as flexible or none was restricted on the studied system and changed from system to system. This index can be utilized in comparing flexibility of various systems or to check the flexibility of a studied system by adding new generators without performing simulation for system operation. This index is fast calculated and depended only on two indicators of thermal generation, the operating range and ramping capabilities of generator. The index is considered a sim-

ple method to evaluate the technical capabilities of system generators to accommodate variable renewable energy sources. While the operation of power system is complicated and variable, operational decisions do not affect this index. The index focuses only on flexible thermal generation whereas the flexible demand and storage were not included in the calculations of this index.

The second offline index known as loss of wind estimation (LOWE), the index was used in evaluating power system flexibility through the calculation of the probability of having wind curtailment in the system during a year. In this index, statistical analysis were performed to calculate the probability of net load to violate system technical thresholds which were the minimum load level and both ramp up and down capabilities. The drawback of this index, it takes only the balancing issues in wind curtailment and not takes into consideration the network or transmission lines constraints in wind curtailment.

In [35], the authors presented a framework to build up a compound metric to provide a precise flexibility evaluation within power system conventional generators. In which eight generating units' physical characteristics were used. The eight indicators can be classified as follows:

1. Two indicators represent the operating range (OR) for each generator which are the maximum output power (P_{max}) and minimum stable output level (P_{min}), measured by MW.
2. Two indicators represent the ramping capabilities for each generator, which represent the average speed that generator increases (Ramp-Up Rate, RUR) or decreases (Ramp-Down Rate, RDR) its output power inside the borders of operating range and measured by MW/h.
3. Four indicators relate to time which are:
 - The start-up time (SUT) measured by hours: which is calculated from turning on the generating unit and synchronizing it to the grid until its output power reaches P_{min} .
 - The shut-down time (SDT) measured by hours: which is calculated from the time that the output power of the generating unit drops below P_{min} to the time when it completely stop.
 - Minimum up time MUT: a conventional generating unit should stay in operation for minimum up time (MUT) after starting-up, almost for economic consideration.
 - Minimum down time MDT: a conventional generating unit should remain offline for a minimum down time to avoid thermal stresses that decrease its lifetime.

The creation of a compound indicator was contained a sequences of stages and each step was needed to be checked, see (Fig.5). An analytic process was applied started by indicators normalization using min-max method, and then weights were assigned to these indicators according to their potential impact in providing flexibility. After that the indicators were aggregated for each generator to provide the compound flexibility index. IEEE RTS-96 test system were used for methodology evaluation. The steps used for evolving this complex metric are explained in details as follows:

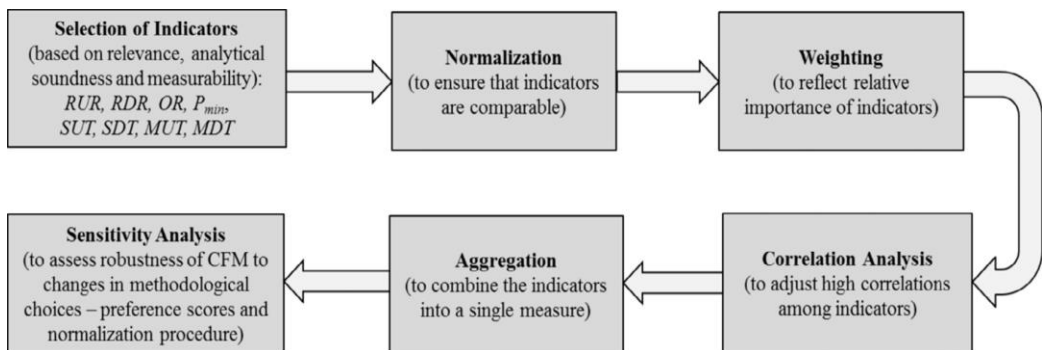


Fig.5. Sequence of steps for building up a compound flexibility metric.

Normalization Step: Indicators of flexibility have diverse units of measurement in addition to their disproportionate scales. Hence for the comparison simplicity and aggregation, normalization should be done. An additional reason is to provide the direction of correlation between the individual indicators and the evaluated phenomenon. For example, the SUT, SDT, MDT, MUT and P_{min} indicators have negative correlation with the flexibility while the RUR, RDR and OR indicators have a positive correlation. Min–max method was chosen for normalization which translates the different indicators values to a unified range inside the interval from 0 to 1 by the following equation:

$$I_{ji} = \frac{X_{ji} - \min_i(X_j)}{\max_i(X_j) - \min_i(X_j)} \quad (7)$$

Where, X_{ji} is the indicator j value for generator i , while $\min_i(X_j)$ and $\max_i(X_j)$ are minimum and maximum indicator j values across all generators i , I_{ji} is the normalized X_{ji} value.

Weighting step: For combining the eight flexibility indicators, weights should be given to reveal the relative importance of each indicator in providing flexibility. The weighting methods are classified to statistic that depend on available trusted database and participatory that rely on expert opinion. In this study, a participatory approach was used because of lacking database. Among the participatory techniques the analytic hierarchy process (AHP) was selected in this study. AHP is commonly utilized by decision-makers when there are multi-criteria (or indicators). Where it based on comparing each pair of indicators with regard to the objective to be achieved so as to extract weights systematically. Then a score from 1 to 9 is used to indicate the importance degree of one indicator with respect to the other indicator. After comparing each pair of indicators, $(N \times N)$ comparison matrix is formed, For N criteria problem; and from which each criterion weight is calculated. As the comparisons number rapidly growing with increasing the criteria number, experts sometimes become inconsistent in their judgments. A consistency ratio (CR) to conserve integrity of the judgments is then calculated together with the weights. The accepted value of CR is 0.10 or less; if not, the comparisons need to be revised.

Correlation analysis step: During allocating indicators' weights, Correlation analysis should be done to examine if there is a high grade of correlation between any two indicators which may lead to a double counted element in the index. For this reason, Pearson coefficient of correlation between each pair of indicators was determined first by using the following equation:

$$r_{xy} = \frac{\sum_i(x_i - \bar{x})(y_i - \bar{y})}{(n - 1)\sigma_x\sigma_y} \quad (8)$$

Where, n is the number of indicators x and y values, \bar{x} , \bar{y} and σ_x , σ_y are their average and standard deviations respectively. If CR is more than a predefined threshold value for a pair of indicators, therefore the weight assigned to that pair should be revised downward in order to prevent over-representation of the common component in these indicators. In the case of the composite flexibility metric, if the r_{xy} value was more than 0.9, the two highly correlated indicators were adjusted during their pair-wise comparisons by decreasing the importance strength of each indicator by one level.

Aggregation step: finally; a linear summation for each normalized indicator multiplied by its relative weight to get the generator index of flexibility as follows:

$$Flex_i = \sum_{j=1}^k (I_{ji} \times W_j) \quad (9)$$

Where, W_j is the weight for indicator j ($j = 1, \dots, k$) subject to $\sum_j w_j=1$ and $0 \leq W_j \leq 1$ and $Flex_i$ is the flexibility index for generator i .

The drawback of this index, it does not take in to consideration the current operational state of the generator. Where, an on line generating unit with high flexibility index could not has the capability of providing more flexibility.

In [36], The Irish power system has wind penetration ranging from 40% to 50% of the electricity consumption. The resulting variability was managed by using a flexibility metric that utilized in operation. The metric was used to estimate the flexibility available in the system for the upcoming hour then comparing it to a variety values of forecasted net load so as to check whether the existing power system resources have the capability to balance ramps in net load in case of the presence of an estimated largely prediction error from historic wind error prediction data.

$$Ramping\ duty + Forecast\ Error = System\ Ramping\ Requirement \tag{10}$$

$$Ramping\ deficit = Ramping\ Requirement - Generator\ Ramping\ Availability$$

In [37], the process flexibility index was introduced by illustrating that the development goal of the almost production processes is producing a feasible manufactured goods that meets specific quality requirements. Between several quality features, production costs and setup time, a preferred trade-off is made. In most applications, the multiple quality features and production costs are joined leading to increase the difficult in getting optimum industrialized set-up. The process flexibility index was used to evaluate the capability of both design and processing variables to achieve large changes in the quality features. This index also used for measuring the process's capability to significantly adjustment the product's quality characteristics that can be used in operations planning problem. The process flexibility metric, Cf , was expressed as "a ratio of the probability that the process will operate within its feasible region to the probability that the process will operate within the specification boundaries."

$$Cf = \frac{\text{volume of feasible space}}{\text{volume of Specification region}} = \frac{v_{feasible\ region}}{v_{Specification\ region}} \tag{11}$$

A graphic representation for the index is illustrated in (Fig.6), in which y_i indicating one of the quality features that has a standard preferred specification constrained by y_i^{max} and y_i^{min} ($y_i^{max} \leq y_i \leq y_i^{min}$) which are the maximum and minimum specification boundary.

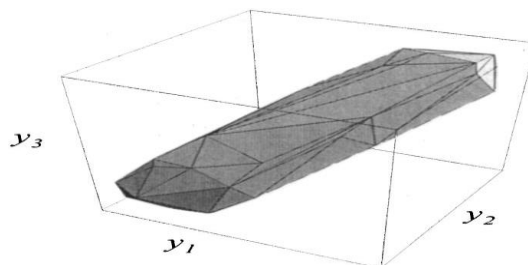


Fig.6. Illustration of process flexibility index.

The possible solutions for all input scenarios were represented in [38] by using the methodology presented in [37] in a multi-dimensional space forming the region of operating (uncut polyhedron), which is not necessary in the system capacity available. Restrictions on physical variables corresponding to the available power resources committed by a unit commitment were shaped the outside borders of a region (cube) of constraint specification. The intersection between the operating region and constraint specification region shaped feasibility region (cut polyhedron) which corresponded to the electric potential needs that provided resources should meet. The ratio of the feasibility region measures to the operating region was termed as an index of flexibility.

$$\text{Flexibility index} = \frac{\text{Volume of cut polyhedron}}{\text{Volume of uncut polyhedron}} \quad (12)$$

The index values ranged from 0 to 1, where 1 denotes the maximum flexibility. The mentioned regions varied according to the studied time, giving a dynamic flexibility index evaluated over time.

The proposed index of flexibility depended on comparing the balance reserves available by unit commitment and dispatching solutions to a group of VRG output scenarios and system demand. A balancing reserve solution is associated with each scenario, provided that preserves a certain level of reliability. But, a single solution is kept for committing in advance. Obviously, one scenario's solution doesn't necessarily meet other scenarios' reliability requirements. The sum of the scenarios probabilities fulfilled by the selected solution strategy defines the index of flexibility. High flexibility index indicates that the majority of other solutions appear below the selected strategy. On the contrary, a solution strategy that has low index of flexibility point out that the majority of candidate solutions are on top of that strategy, see (Fig.7).

The drawback of this metric is that it pre-supposed the calculations of a variety of unit commitment scenarios for each period which increase the computational efforts required.

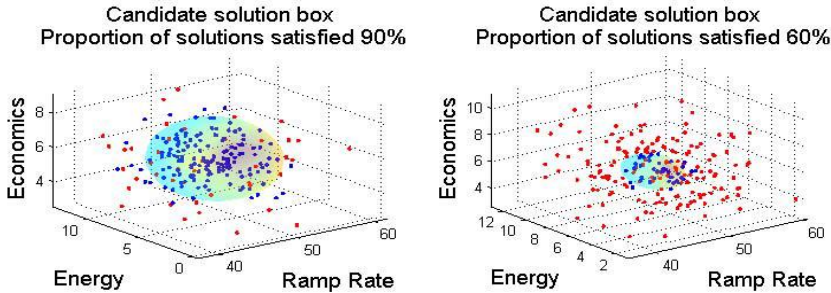


Fig.7. Comparison between high and low flexibility index for a candidate solution strategy.

In [2], the authors proposed a metric known as IRRE (insufficient ramping resource expectation) which utilized in evaluating the flexibility of a power system in the planning stage. It was deduced from the indicators of generation adequacy.

In this index, the ramping in net load time series, $NLR_{t,i,+/-}$ is determined in each time horizon then divided to up (+) and down (-) net load ramps.

$$NLR_{t,i} = NL_t - NL_{t-i}$$

$$1 \leq t \leq |NL| - i$$

$$NLR_{t,i,+} = NLR_{t,i} \forall NLR_{t,i} > 0$$

$$NLR_{t,i,-} = -NLR_{t,i} \forall NLR_{t,i} < 0$$
(13)

Where, i indicates the time interval, t indicates the observation time and $|NL|$ indicates the net load time series length.

An offline resource provide flexibility, if its startup time, S_r , is short compared to the studied time horizon with adequate time for reaching the minimum level of stable generation. If a resource achieves this constraint, the available upward flexibility $flex_{t,r,i,+}$ is determined by multiplying its ramp up rate, $RR_{r,+}$, by the residual time that results from subtracting its startup time (S_r) from the studied time horizon (i). For online resource, the ramp up rate, the minimum and maximum levels of stable generation, $Gen_{MAX/MIN,r}$, are the necessary constraints on the available flexibility.

The upward (+) available flexibility ($flex_{t,r,i,+}$), for a resource r , over time horizon i , at observation time t in the net load ramp time series is given by,

$$flex_{t,r,i,+} = RR_{r,+} * (i - (1 - Online_{t,r}) * S_r)$$

$$P_{t,r} + flex_{t,r,i,+} \leq Gen_{MAX,r}$$

$$P_{t,r} + flex_{t,r,i,+} \in R \setminus (0, Gen_{MIN,r})$$
(14)

Where, $P_{t,r}$ is the resource r output power on the time of observation, t , and $Online$ indicates the boolean online resource variable.

Of course there is no downward flexibility $flex_{t,r,i,-}$ for the offline resource. The downward flexibility available for online resources are constrained by ramp down rate ($RR_{r,-}$) and minimum level of stable generation. The downward available flexibility from each resource r at each time of observation, t , is calculated as follows:

$$flex_{t,r,i,-} = RR_{r,-} * i * Online_{t,r}$$

$$0 \leq P_{t,r} - flex_{t,r,i,-}$$

$$P_{t,r} - flex_{t,r,i,-} \in R \setminus (0, Gen_{MIN,r})$$
(15)

For each resource, once both upward and downward flexibility are determined for wholly studied time horizons, the system flexibility time series ($flex_{t,SYSTEM,i,+/-}$) is calculated as follows:

$$flex_{t,SYSTEM,i,+/-} = \sum_{\forall r} flex_{t,r,i,+/-}$$
(16)

The available flexibility distribution ($AFD_{i,+/-}(X)$) is deduced from $flex_{t,SYSTEM,i,+/-}$ by using Kaplan-Meier estimator of cumulative density functions and indicating the likelihood that a power of X MW or lower will be available from a flexible power resource during the time horizon i [39]. From $AFD_{i,+/-}(X)$, the insufficient flexibility probability for each observation time can be calculated which represent the cumulative probability which a power system failed to meet ramping required in the net load at that observation time. In order to eliminate cases at which just enough flexibility is available in $AFD_{i,+/-}(X)$, the net load ramp time series magnitude is reduced by 1MW. Hence, the insufficient ramping resource probability ($IRRP$) is given by:

$$IRRP_{t,i,+/-} = AFD_{i,+/-} (NLR_{t,i,+/-} - 1) \quad (17)$$

After that the insufficient ramping resource expectation, $IRRE_{i,+/-}$ is obtained by summing the values of $IRRP_{t,i,+/-}$ over the whole time series, $T_{+/-}$, for each ramp direction as follows:

$$IRRE_{i,+/-} = \sum_{\forall t \in T_{+/-}} IRRP_{t,i,+/-} \quad (18)$$

The authors in [31] studied system flexibility in planning stage. Hence some assumptions were supposed concerning each unit operation. Such as the operation of power resources was dependent on the merit order dispatch, by which electricity demand was supplied by dispatching generation units at the maximum generation from each power resource according to the incremental marginal cost of energy. Hence, in the decisions of unit commitment, the constraints of forecast errors, start-up costs and ramp rate were not included since the process was non-chronological. Moreover, the effects of transmission line network constraints were not included. Although ramps in net load may be up or down, the upward flexibility was examined only. Because net load down ramps could be met by several options such as ramping down the output power of generating units, reducing excess power from renewable energy by VRG curtailment or by exporting excess power to adjacent areas or increasing electricity consumption, While these options may be not available for ramping up. The proposed methodology determines the periods of flexibility deficit and requires from each flexible resource in a system such as power generators, systems of energy storage, demand side response (DSR), and from interconnection of adjacent areas, the output power time series. The periods of flexibility deficit were calculated as follows:

- a) The average cost (AC) for every unit of generation or storage at maximum power output was determined, and then the resources of power system were arranged in ascending order in accordance to the increase in marginal costs of full load to form the merit order supply function [40].

$$AC = \frac{Noloadcost (NLC)+CAPACITY*MarginalCost (MC)}{CAPACITY} \quad (19)$$

- b) The net load time series were calculated by subtracting the output of variable generation from the system demand at each time of observation.

$$NL_t = system\ demand_t - \sum VG_t \quad (20)$$

- c) The ramps in net load (NLR) were determined in net load time series at every observation time.

$$NLR_{t,i} = NLR_{t+i} - NLR_t \quad (21)$$

$$1 \leq t \leq |NL|$$

- d) The net load duration curve, NLDC, was formed by arranging the net load in descending order. For system reserve provision, addition of reserve required to NLDC could be included. After that the net load was supplied by adding resources one after the other starting with the least cost according to the merit order and by taking into consideration minimum stable generation level for each generator (MSG). If the scheduled operation of a generator was less than MSG, the output power from the previous online generator was decreased by the output power resulted from subtracting the scheduled output of that generator from MSG. Hence, generator output was increased to its MSG.
- e) The online power resource available flexibility, $F_{t,i,r}^{Online}$, was determined by calculating maximum increasing in a resource output power, for the studied time horizon constrained by the rated power output and initial output power for that power resource at each observation time which calculated by using the following equation:

$$F_{t,i,r}^{Online} = Online_{t,r} \times \min(RR_r \times i, Ratedcapacity_r - P_{t,r}) \quad (22)$$

Where, t indicated to observation time in NLDC, $RR_r, P_{t,r}$ the resource, r , ramp rate and its output power at observation time, t . The flexibility available from an offline resource if it can be synchronized and start production within the selected time horizon is given by:

$$F_{t,i,r}^{Offline} = \min(RR_r \times (i - S_r), Ratedcapacity_r) \times (1 - Online_{t,r}) \quad \forall i \geq S_r \quad (23)$$

To calculate the time series of the flexibility available for a power system. The summation of both offline and online available flexibility for every power resource was added.

$$F_{t,i}^{available} = \sum_{r=1}^R F_{t,i,r}^{Online} + \sum_{r=1}^R F_{t,i,r}^{Offline} \quad (24)$$

Where, R was indicated to the total power resources number.

The drawback of dispatching generators by merit order method was the exaggeration the system's flexibility so the results in reality were sub optimal. Since the merit order commitment is non-chronological, therefore for each time interval, the power system costs were minimized, while unit commitment solutions take many other factors such as demand forecasting of next periods and starting-up time, cost, and ramping rate for every power resource. Consequently, dispatching more expensive fast-starting, resources out-of-merit are possible for avoiding starting-up huge power resource that is only required for a small time period. Therefore reducing the flexibility available online and offline with respect to the merit order method.

As a result, an improvement to the previous method for more realistic results was done by mixing between merit order and economic dispatch methods. In which all power resources were dispatched by merit order in condition that their maximum power output were less than the net load level. The remaining resources were dispatched for supplying the residual of net load according to the economic dispatch method to reduce the total cost. For each power resource, the flexibility in NLDC at every point was determined as illustrated before. A power system was considered had a shortage in flexibility or net ramping resource deficit, $PF_{t,i}$, when $NLR_{t,i}$ was greater than flexibility available $F_{t,i}^{available}$ which equivalent to the *IRRE* outlined in [2].

$$PF_{t,i} = NLR_{t,i} - F_{t,i}^{available} \quad (25)$$

Both $PF D_{i,+/-}$ and $IRRE_{i,s,+/-}$ metrics measure the system flexibility, but differ in the assumptions relating to the risk level and $PF D_{t,i}$ is deterministic but $IRRE_{i,+/-}$ is a probabilistic metric. From the previous equation, some metrics were calculated to describe the system flexibility. For example, to exhibit the outage effect of individual units, $IRRE_{t,i}^{MERIT/HYBRID}$ was calculated and repeated for each resource removed from the group in every time horizon i.e. repeating the calculations for $(R + 1)$ times. For the majority of time horizons, $IRRE_{t,i}^{MERIT/HYBRID}$ values were higher as the available flexibility were supplied by a smaller number of power system resources.

The drawback of this method was that the transmission line thermal limits and security constraints were not included in calculations.

In [41], the authors presented a metric for power system planners to calculate both upward and downward flexibility and to demonstrate the effect of transmission line networks on the flexibility by calculating maximum realizable flexibility. The upward flexibility $F_{t,r}^{+,h}$ and the downward flexibility $F_{t,r}^{-,h}$ were calculated as follows:

$$F_{t,r}^{+,i} = RR_r^+ * (i - (1 - Online_{t,r})) * S_r * A_{t,r}$$

$$P_{t,r} + F_{t,r}^{+,i} \leq Gen_{MAX,r} \quad (26)$$

$$P_{t,r} + F_{t,r}^{+,i} \geq 0$$

$$F_{t,r}^{-,i} = RR_r^- * i * Online_{t,r}$$

$$P_{t,i} - F_{t,r}^{-,i} \geq 0 \quad (27)$$

$$P_{t,i} - F_{t,r}^{-,i} \geq Gen_{MIN,r}$$

Where, $Gen_{MAX,r}$, $Gen_{MIN,r}$ were indicated to the maximum and minimum generation for every resource r respectively, the availability of each resource (r) at time (t) denoted by $A_{t,r}$ and $Online_{t,r}$ was the binary online state variable for each resource.

If the power system network is not congested, all flexibility available from every power system resource that scheduled for operation will be realized. But in fact the total realized flexibility may be lower than that typically available because the flexibility estimation methods was depended on the resource schedules alone [2]. Which had led to an overestimation of system flexibility. For calculating realizable flexibility, an analysis for power system network should be performed by a specialized computer programs [42] [43]. Optimization process used in calculation of maximum allowable power system flexibility under a variety of conditions for all time periods. The maximum demand that can be added to a power system and balanced by the system power resources without breaking either the generating units or the network restrictions was defined as the maximum flexibility that can be realized for that period of time, RF . The maximum realizable flexibility for each scenario (S) of VG output (RES) for each VG resource (v) at a selected time horizon (i) and at every period of time (t) was calculated. Upward realized flexibility was determined by adding the difference between total output power (P) of flexible resources at each point in time and the total power output once the selected time horizon was passed to the alteration of VG output power during the same time horizon as follows:

Maximize $RF_{t,i,s}$

$$RF_{t,i,s} = \sum_{r=1}^R P_{r,t+i,s} - \sum_{r=1}^R P_{r,t,s} + \sum_{v=1}^V RES_{v,t+i,s} - \sum_{v=1}^V RES_{v,t,s} \quad (28)$$

Where the number of flexible resource and the total number of them were indicated by $\{r, R\}$ respectively.

Through optimization process, net demand, and consequently, flexible power resources output power were increased until reaching either the network or the flexibility limitations. In that case, the maximum flexibility which could be realized (RF) upwards was determined. After that, optimization process path was altered for calculating the flexibility which could be realized downward by minimizing realized flexibility [24]:

Minimize $RF_{t,i,s}$

$$\begin{aligned} P_{r,t+i,s} &\leq P_{r,t,s} + F_{r,t,s}^{+,i} \\ P_{r,t+i,s} &\leq P_{r,t,s} - F_{r,t,s}^{-,i} \end{aligned} \quad (29)$$

The output power was constrained by the resource's flexibility boundaries for each flexibility power resource at the end time horizon. So, the output power change couldn't surpass the flexibility boundaries for either upwards or downwards, $F_{r,t,s}^{+/-,i}$, and included resources online as well as offline. Also network limits were included for ensuring the balance between demand and generation in addition to prevent breaching the line flow limits and preservation of power in the network.

$$\begin{aligned} \sum_{n=1}^N FinalDemand_{n,t,s} &= \sum_{r=1}^R P_{r,t+i,s} + \sum_{v=1}^V RES_{v,t+i,s} \\ FinalDemand_{n,t} &= \sum_{v=1}^V PlantAtNode_{n,v} * RES_{v,t+i,s} \\ &+ \sum_{r=1}^R PlantAtNode_{n,r} * P_{r,t+i,s} \\ &+ \sum_{l=1}^L LineAtNode_{n,l} * FD_{n,l} * LF_{l,t,s} \\ LF_l^{MIN} &\leq LF_{l,t,s} \leq LF_l^{MAX} \\ LF_{l,t,s} &= -\frac{1}{X_l} \sum_{\substack{n=1 \\ b=1 \\ b \neq n}}^N [\delta_{n,t,s} - \delta_{b,t,s}] \end{aligned} \quad (30)$$

In the previous equation, $\{n, b\}$ indicated to the index of every bus in the system and connected buses respectively, $\{LF_{l,t,s}, \delta, FD_{n,l}\}$ indicated to the flow in line l , every bus phase angle and flow direction on line $\{l\}$ at bus $\{n\}$ respectively. The maximum system demand that the power system able to meet with end of time horizon was represented by $FinalDemand_{n,t}$.

Therefore the realized flexibility was estimated by considering three of varied parameters: both of them were time dependent (t, i) and the other varied parameter was the scenario of VRG output power (s) .

The system requirement of flexibility was determined by net load ramp time series $NLR_{t,i}$ at every time period (t) in every time horizon (i) , as follows:

$$NLR_{t,i} = NL_{t+i} - NL_t$$

$$1 \leq t < |NL_t| \quad (31)$$

A different flexibility amount was deployed according to ramps in VRG for every scenario until the line flow boundaries were reached. Hence, different flexibility values was estimated according to the studied scenario and the expected values were taken at every time period to represent flexibility of the system. The index of flexibility deficit periods ($PFDS_{s,i,+/-}$) counted the time periods number at which the summation of the requirements of both net load ramping ($NLR_{t,i}$) and contingency reserve ($Contingency_t$) exceeded the realized flexibility ($RF_{t,i,s}$) for each ramp direction. Index of $PFDS_{s,i,+/-}$ calculated for each scenario and after that the $PFDi,+/-$ for that time horizon and direction was taken as the average of all scenarios values.

$$NetFlexibility_{t,i,s,+} = RF_{t,i,s} - (Contingency_{t,+} + NLR_{t,i})$$

$$NetFlexibility_{t,i,s,-} = NLR_{t,i} - Contingency_{t,-} - RF_{t,i,s}$$

$$PFDS_{s,i,+/-} = \# NetFlexibility_{t,i,s,+/-} < 0. \quad (32)$$

$$PFDi,+/- = Mean(PFDS_{s,i,+/-})$$

The drawback of this index was that transmission line thermal limits and security constraints were not included in calculations.

In [44], wind and solar power that integrated with different combined penetration levels (10%, 30%, 50% and 70% of annual demand) in Europe were discussed. A power system that has a VRG penetration level of 70% was considered a completely renewable. The PV share was set at 20%, 40% and 60% for every level of penetration. The study showed that increasing wind/PV penetration above 30% increased flexibility requirements. Particularly when PV contribution in the wind/PV mix was above 20-30%. Analysis had been concluded that future requirements of flexibility in Europe would be affected by three main factors: (1) percentage penetration of VG. (2) The VG technology mix. (3) The system geographic distribution size.

The important element was the power ramps $\Delta_i P(t)$, which described by power variation in a studied interval of time of (i) hours:

$$\Delta_i P(t) = p(t) - p(t - i) \quad (33)$$

Where $P(t)$ represented output power at time t from a spatial wind / PV unit (region or country), $t = \{i+ 1, \dots, 8760\}$. Net load power ramp rates were determined for every country as function of load, wind and PV ramp rates:

$$\Delta_i NL(t) = \Delta_i L(t) - \frac{\alpha \beta D}{8760 \mu_{pv}} \Delta_i PV(t) - \frac{\alpha (1 - \beta) D}{8760 \mu_w} \Delta_i W(T) \quad (34)$$

In the previous equation,

$\Delta_i NL(t), \Delta_i L(t), \Delta_i W(t), \Delta_i PV(T)$ symbolized the power ramps in net load, load, wind and PV respectively. Annual consumption was denoted by D , $\{W, PV\} \in [0, 1]$ represented the power of wind and PV that was normalized to the installed capacity. μ_w, μ_{pv} denoted the average power output from wind and PV over one year. The aggregated contributions of wind / PV energy to the consumption of annual electricity was represented by α . The aggregated PV output power contribution in the aggregated contribution from wind and PV was denoted by β as follows:

$$\alpha = \frac{\sum_{t=1}^{t=8760} P_{Wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)}{D} \quad (35)$$

$$\beta = \frac{\sum_{t=1}^{t=8760} P_{PV}(t)}{\sum_{t=1}^{t=8760} P_{Wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)}$$

For performing a comparison between countries, all occurring ramps in every country were determined as a percentage from the peak load. The system requirements of flexibility were evaluated depending on the following factors:

- (1) The level of VG penetration and the share of wind and PV in wind/PV generation, (α, β) as choosey variables selected by decision makers.
- (2) The power ramp behavioural characteristics of load, PV and wind which affected by geographic location, the positioning of the generator and the size of the system.
- (3) The correlation between ramps in VG and load and also between wind and PV ramps.

In [45], a chart of flexibility was developed which presented a simple, nontechnical means for quickly identifying the potential of the system's flexible power resources. In which the installed capacity percentage of five flexibility power sources including combined cycle gas turbine, hydro, pumped hydro, combined heat and power (CHP) and interconnection relative to the peak demand were indicated in the chart. However, the chart was just for indication and did not include the calculation of overall flexibility of power system. The *International Energy Agency*, IEA, designed a simple computation flexibility assessment tool, FAST, which utilized as a measure of requirements for flexibility and power resources in various power system areas with different VRG penetration levels [46]. In 2014, IEA presented FAST2 which was a modified version of FAST with many timescales flexibility assessment [47]. More data was needed by FAST2. For example, conventional unit flexibility features, the information about DSM and interconnection. FAST2 determines maximum alteration in the balance between generation and demand at a given instant which a power system able to meet. In addition to the ability of computing the VRE integration level at which more flexibility is needed.

The Electric Power Research Institute, EPRI, made a framework consists of four flexibility evaluation levels at various stages of power systems long-term planning process [48] [49].

Another tool that has multi - level flexibility evaluation called InFLEXion was designed for facilitating decision - makers understanding of the need for flexibility of the power system. Four flexibility metrics were included in InFLEXion tool which are *IRRE*, *PFD*, expected unserved ramping (EUR) and wellbeing assessment. EUR evaluates the total flexibility shortage magnitude rather than duration. It determines over a certain time horizon the aggregate deficits of power ramping. Well-being analysis used the deterministic and probabilistic indicators in diagnosing the power system state from the following states: at risk, marginal or healthy [28]. Similarly, InFLEXion tool evaluates the flexibility shortages magnitude and frequency over a specified time period using PFD and EUR to decide whether the state of a power system is safe, warning, or dangerous [49].

The authors in [48] noted that the earlier studies concentrated mostly on the operating problems of the power system and did not address the power system economic considerations of addition resources of flexibility. As a result, a simulation model for stochastic production was made which identified as REFLEX, Renewable Energy Flexibility. In which a variety of power system reliability and flexibility indices were used in characterising the flexibility expected and shortages of adequacy in the system. After that REFLEX evaluates the optimum investments of flexible capacity by comparing the addition costs of flexible resources with the improvement obtained as a result of avoided violations of flexibility. Which assisted planners of power systems in determination of least-cost capacity strategy to face challenges introduced by the integration of VRE in various timescales. Power system available flexibility improvements required added costs. Several researches tried the estimation of the flexibility provision cost which is important in selecting the optimal expansion plan [51][52][53].

Some of power system flexibility metrics were derived from the generation adequacy indices. The authors in [54] used the effective load carrying capability, ELCC, method that utilized in measuring the added load which the power system able to supply with particular generator with no net change in reliability [55][56] to suggest the effective ramping capability metric, ERC, that used in the estimation of new generating unit contribution to overall power system capacity; in addition to the approximation generating unit contribution to the ramping capacity of overall power system.

In [21] [22], the authors used dynamic envelopes in characterizing the provision and requirements of flexibility, The authors assert that by enclosing the envelope of flexibility requirement formed through net load observations by the envelope of aggregated flexibility that shaped by flexibility power resources sufficient power system flexibility will be achieved.

In [23], a new expression called locational flexibility was introduced for describing the power system capability in containing a certain node disturbance. A unified framework for quantifying and comparing flexibility available with forecast uncertainty was presented. The presented case studies illustrated that flexibility was varied at diverse grid locations, it also illustrated that the use of energy storage units and the curtailment of renewable energy could be effective means to increase flexibility locally.

The authors in [24] presented a framework that focusing on the reserves available and the flows of tie - line for characterizing the available operational flexibility in a power system of multi - area which similar to the available transfer capacity, ATC, but (N-1) security criterion were taken into consideration. The proposed approach discussed the flexible resources contribution in adjacent areas to handle the occurred contingencies in a certain area. Hence the term “exportable flexibility” was introduced to measure the flexibility that one area can introduce to its neighbors. If the available flexibility is shared between different power system areas, the system can handle larger variations which permits more integration of VRE sources. The drawbacks in the methodology were in the calculation of the available flexibility, which was based on the assumption that the power system demand was covered and the operational restrictions were achieved. In addition to, for validating the methodology more examples that focusing on the generalization of the methodology to more than two areas are required.

In [57], the lack of ramp probability (LORP) was proposed, like LOLP which utilized for measuring capacity adequacy, to measure the system capability in meeting net load changes in real time. LORP relied on the likelihood of meeting the expected next period of net load from the present generator schedules, considering the inter temporal schedules increments of both imports and exports interconnection, in order to add the positive import and negative export increases as ramp - up capacity. The system $LORP_s$ for ramp up was expressed as follows:

$$LORP_s^{up,\tau}[t] = Pr\left(\sum_{i \in I} \{P_i^g[t] + \min(\tau R_i, P_i^{max} - P_i[t])\} < P_s^l[t + \tau]\right) \quad (36)$$

The system $LORP_s$ for ramp down was expressed as follows:

$$LORP_s^{dn,\tau}[t] = Pr\left(\sum_{i \in I} \{P_i^g[t] + \min(\tau R_i, P_i[t] - P_i^{min})\} > P_s^l[t + \tau]\right) \quad (37)$$

Where, $P_s^l[t + \tau]$ is the system net load for time step τ in the future. The zone ramp up capability, RC_z , for $\tau = 1$ was expressed as follows:

$$RC_z[t] = \text{Zonal Generator Ramp Power}[t] + (\text{Import}[t + 1] - \text{Import}[t]) - (\text{Export}[t + 1] - \text{Export}[t]) \quad (38)$$

The LORP for zone ($LORP_z$) was expressed as follows:

$$LORP_z^{up}[t] = Pr(\sum_{i \in I^z} P_i^g[t] + RC_z[t] < P_z^l[t + \tau]), \forall z \quad (39)$$

The available system flexibility of the proposed metric was computed in two-steps: (1) The network was reduced first by considering each zone as a single bus with net injection in which all generators and loads were connected to this bus and the transmission lines flow limits of the zone were ignored and the tie lines between each pair of zones were aggregated to an equivalent single tie line. Then in the first step, the generation was dispatched for meeting the net load of current time period, plus the worst case of the following ones taking into consideration uncertainty and ramps limits. (2) In the second step, the flow limits of the tie-lines were partially relaxed based on acceptable selected short-term flow violation for the tie line which selected by system operator, and for the all system, a deterministic optimization economic dispatch was executed with keeping the ramp capability of the zones at the same values determined in the first step.

For current time interval and future time intervals the generator dispatch solutions were obtained each time the two-step economic dispatch was solved. The current interval solution was implemented whereas the future interval solutions were considered as recommended. After that the process is repeated by moving forward in time, and taking the updated forecast information of load and renewable generation.

The drawback of this method, since the constraints of intra-zonal flow were not considered in step 1 of the dispatch model, all realizations of net load uncertainty were not taken into consideration by the dispatch solution. Therefore, shortage events were reduced but not eliminated completely.

The authors in [58] [59] estimated the flexibility range for the next hours at each primary substation node. In which, the feasible resources of flexibility that available in distribution grid that originated from actions of flexibility (demand response, flexible distributed generation, or control of reactive

power from the distribution system operator (DSO) assets) were informed to the transmission system operator (TSO). The costs of activating these resources of flexibility were also considered to carry out a cost - benefit assessment of the available actions.

The authors in [60] proposed new metrics for evaluation power system flexibility by involving the electric vehicles (EV) into the flexible ramp market. The impact on power system reliability and flexibility were evaluated, for both electric vehicles direct participation and by cooperation with conventional generators.

In [18], the indices proposed by the authors were included: loss of flexibility probability (LOFP), loss of flexibility duration (LOFD), loss of flexibility expectation (LOFE) and flexibility demand shortage (FDS). The LOFP is seemed similar to LORP and IRRE but LOFP is independent with time and LORP and IRRE are time varying. So do as LOFD and LOFE compared to PFD and ENS. The indices have the following characteristics:

- 1) In case of upward flexibility, the relationship between the index and load loss is linear and so as with RE curtailment in case of downward flexibility. The proposed flexibility indices can be determined, once the acceptable curtailment limit was determined,
- 2) The indices can be used with diverse options of flexibility such as units of conventional generating and energy storage.

Conclusion

Flexibility metrics in power systems are ranged from simplicity to complexity according to the indicators and constraints that were taken into consideration during evolving the metric and according to whether the metric was used in operation or planning stages. Although several metrics of flexibility and techniques of evaluation were existed, up - till - now there is no flexibility metric that taken as a standard. Consequently, metrics are still developing.

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