Assessment of Power System Flexibility: A High-Level Approach

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Abstract—**The targeted growth of variable generation capacity in many power systems has led to concern that future systems may have insufficient flexibility to meet ramps in variable generation (VG) production and system demand. This paper introduces a high-level flexibility assessment methodology for use by those involved in planning, and with little experience of the integration of large quantities of variable generation. This is proposed as a first step in assessing the future needs of a system. Comparison is drawn between the proposed high-level flexibility assessment and a more detailed flexibility assessment. The insufficient ramp resource expectation (IRRE) highlights those time horizons in which the system may have insufficient flexibility to meet changes in the net load. The methodology is demonstrated on a test system from which high-level conclusions may be drawn. A number of other insights are also offered by the proposed methodology, including the distributions of the size of the deficit, and surplus, of ramping capability.**

Index Terms—**power system modeling, power system planning, wind power generation, solar power generation, hydro power generation**

I. INTRODUCTION

In response to environmental, economic and security of supply concerns regarding the dominance of fossil fuels usage in the energy mix of many countries, significant growth has been witnessed in the amount of installed wind and solar generation capacity [1], [2]. With the advent of policy initiatives such as the EU renewables directive [3], renewable portfolio standards [4] and other national policies, electrical power systems are undergoing a period of substantial physical change. This is set against a context of recent regulatory change to the operation of electricity markets, through market liberalization in the European countries, experiencing strong growth in variable generation (VG).

A consequence of liberalization is that independent power producers (IPP) have now become responsible for investment in generation, as national vertically integrated utilities are unbundled. Market participants face challenges in identifying the needs of the system in years to come, and assessing the risk associated with the forecast requirements. In many systems, long-term demand projections have proven to be inaccurate in the face of economic turbulence, with a corresponding increase in investment risk.

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A new issue for IPPs and regulators, charged with maintaining the reliability of a system, is to assess the needs of a system due to the integration of variable generation. The introduction of VG may have a material impact on the operation of an IPP's assets through changed market rules and increased cycling requirements [5]. While some systems have built up experience of system operation with significant penetrations of variable generation (e.g. Denmark, Ireland, Portugal, Spain, BPA, ERCOT), many systems lack such insight into cycling and ramping requirements of their generation assets. There is a risk, therefore, that potential investment options may be unsuitable for operation in generation portfolios with high penetrations of VG, and may become redundant as operational practices or ramping mitigation strategies evolve.

As experience with the operation of VG has increased, considerable effort has been directed towards characterizing the consequent increase in the variability of net demand [6]. Prevailing environmental conditions have an effect on the correlation between VG and system load; since VG has priority dispatch status in many countries, the remaining generation must meet the net load, where the net load is defined as the system demand not met by variable generation. Current research is focusing on quantifying the variability of the net load, since net load ramps must be met by conventional, dispatchable resources. The insight provided by such analysis is valuable to system operators, generation plant manufacturers, IPPs and regulators alike and may help to determine the ramping and cycling which future generation, interconnection and electricity storage resources may be required to meet.

With the data and experience acquired to date, planning entities have begun the process of identifying the physical and institutional changes which will be required by high penetrations of VG in a power system [7], [8]. Since generation units are not the only option for managing variability, system operators and regulators have sought new methods to determine whether current infrastructure and policies will suffice, and to identify the least cost portfolio which meets the new requirements of a system.

An example of the evolution of operations with increased VG penetration is the development of new methods to calculate the optimal amount of operating reserve. While sufficient reserve has been traditionally carried to meet system demand forecast errors and generation or transmission outages in a system, newer methods have been developed to include the effect of VG forecast errors [9], [10]. However, these methods do not measure a system's ability to provide the reserve in actual operation.

The concept of system flexibility has been introduced in order to complement traditional capacity adequacy planning

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[8], [11], [12]. Flexibility is the ability of a system to use its resources to meet changes in the net load, and so is considerably different from the capacity adequacy of a system. While the latter is a function of the amount of capacity available, the forced outage rate of each resource and the system demand, system flexibility is affected by many additional factors, such as the generation portfolio, the availability and ramp rate of resources, the magnitude and frequency of net load ramps, the predictability of net load variations, interconnection to other systems, the presence of energy storage, demand side resources (DSR), the market arrangements in place and reserve provision strategies [8], [12], [13].

Furthermore, a system's requirement for flexibility changes depending on the time horizon studied, where a time horizon is defined as the duration of a net load change. For example, a system will have a smaller requirement for flexibility over a 10 minute time horizon when compared to a change in net load lasting 12 hours, as Figure 1 shows based on wind data in the Ireland during May 2011. The resources available to provide flexibility to a system are also dependent on the time horizon to be studied. For example, an offline unit may be able to come online and commence production in 6 hours, but not in a 30 minute time horizon. Since the relationship between the net load ramp magnitude and the time horizon is non-linear, separate analyses are required for individual time horizons as results for one time horizon cannot be linearly scaled to infer results in another.
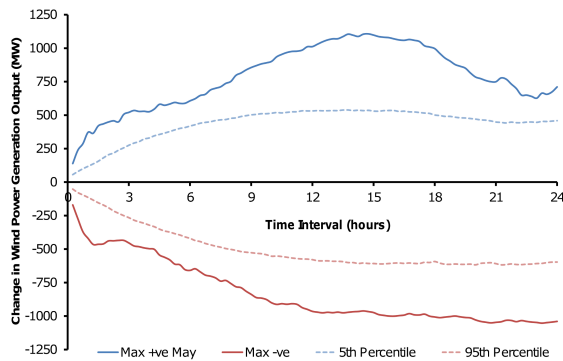

Fig. 1.   Wind ramp mangitudes as a function of the time interval, Ireland, May 2011

Two systems with the same net load profile and installed generation capacity, but with differing technology mixes will manage the variability of the net load to a different extent. Nuclear and coal units tend to operate in base load conditions for long periods and cannot change their output quickly, compared to a open cycle gas turbine. A system with a greater number of flexible resources should be able to integrate VG more successfully.

In order to determine a system's ability to meet changes in net load, VG integration studies have been carried out in many systems worldwide [14]–[17]. These integration studies typically involve the simulation of the behavior of a system, for a number of scenarios, in a production cost model. Using time series data for load, VG production, fuel prices and generator availability, integration studies have demonstrated how different portfolios of generation, interconnection, DSR

and energy storage might perform in reality. The results may also show the impact of a change of operational policy such as the unit commitment procedure or reserve requirement. However, integration studies require extensive data and are computationally intensive in nature. Therefore, the number of sensitivities carried out may be limited and the operational limits of a system may not be reached. This has led to the development of long-term planning metrics to determine the flexibility of a system.

One such metric is the insufficient ramping resource expectation (IRRE), which has been developed as a flexibility metric for the long-term planning time frame [13]. The IRRE is the expected number of times in a given period that a system will not be able to meet changes in the net load. In order to recognize the many factors affecting flexibility, the IRRE requires the production time series of all flexible resources (e.g. generators, DSR, energy storage, interconnection) in a system. The methodology presented in [13] requires the simulation of system operation using computationally intensive unit commitment. Once the availability and production of each resource is known, a distribution of the probability of flexibility available in the system is calculated, from which the probability of insufficient flexibility to meet each ramp is determined. The IRRE, calculated in this way, depends on considerable offline data gathering and computational analysis, and is not suitable for high-level aims. A high-level methodology to determine the IRRE, with no requirement for intensive production cost simulation, is presented in this paper which would be more suitable for policy makers and system operators just commencing the VG integration process.

This paper seeks to determine the flexibility of a system without resorting to full production cost modeling. The system flexibility will be measured using a high-level IRRE algorithm, outlined in Section II. Section III describes the test system to be studied and presents the results of the analysis for the test system. Section IV discusses these results and the further developments to the proposed methodology, and Section V concludes.

II. METHODOLOGY

A high-level methodology to quantify the flexibility of a generation portfolio is sought, in order to eliminate the need for computationally intensive production cost simulation. However, the unused capacity available at any observation in time is dependent on the state of each resource in a system. Without detailed simulation of a system, assumptions about the operation of each unit are required. The assumption is made in this paper that system resources are operated according to a merit order dispatch, whereby the load is met at each observation in time by dispatching units based on the incremental marginal energy cost from each resource at maximum output. Since the process is non-chronological, ramp rate constraints, start-up costs and forecast errors are excluded from commitment decisions.

Furthermore, the impact of transmission network constraints and institutional procedures on the availability of flexibility from a system's resources are not included, as a result of the merit operation assumption. However, the purpose of this

paper is only to provide a high-level insight into the flexibility of a system before more detailed studies are carried out.

A. Generation flexibility assessment method

Using a merit order to estimate the production of all resources, the amount of flexibility available at each observation in a net load time series can be calculated for a system, which can then be compared to the net load ramps coincident in time. The number of periods in a year when a system has insufficient available flexibility is then counted to give the insufficient ramping resource expectation for a given time horizon ($IRRE_i^{MERIT}$). While net load changes can be both upward and downward, upward flexibility is examined exclusively here. Downward changes in net load can be managed by down ramping of units, curtailment of VG or an increase in exports or consumption. hence, the system operator should always have an option available to deal with decreasing net load, whereas the same options are not guaranteed to be available for the upward ramping case. A detailed description of the methodology is given in the sections that follow.

B. Data requirements

The system flexibility assessment method requires information on the resources which provide flexibility to the system, and on the system demand and VG production which require flexibility. A time series of system demand and variable generation coincident in time, at the resolution of the smallest time horizon to be examined, is required. Details required for generation units include the capacity, minimum stable output, ramp rate, start-up time, forced outage rate and the energy price at maximum output for each resource. Finally, the reserve targets for regulation and contingencies should also be known. In order to fully understand the challenge each power system faces a number of time horizons are chosen to be studied, based on the availability of data, or significant operational time horizons, such as the start up time of a dominant generation type or a forecast horizon.

C. Including operations

The first part of the process is to calculate the flexibility available from the individual flexible resources. By ordering the resources according to increasing full load marginal costs of energy from each resource, the merit order supply function for energy can be calculated [18]. The changes in net load ramps (NLR) are then calculated for each observation in the net load time series (equation 1).

$$NLR_{t,i} = NLR_{t+i} - NLR_t \tag{1}$$

$$1 \le t \le |NL|$$

where t is the observation in the net load time series, i is the time horizon and $|NL|$ is the length of the net load time series. The net load is then sorted in order of decreasing net load, resulting in the net load duration curve (NLDC) and the

changes in net load coincident with each net load level are noted. If the system makes provision for reserve, the target amount of reserve required for the time horizon under scrutiny is added to the NLDC, effectively increasing the net demand.

Using the merit order and the net load duration curve, the production levels for each resource are then calculated at each observation in the NLDC, as shown for a simple three unit system in Figure 2. This is achieved by sequentially adding each resource, according to the merit order, until the net load is met. Unit 3 is the most expensive, unit 1 is the cheapest to run and all units are assumed to have a minimum stable output of 0 MW. Point A in Figure 2 represents the net load level which can be met by unit 1 operating at maximum capacity. At net load levels between points A and B, unit 2 is also required. At net load levels higher than point B, all units are required in order to meet the net load. The grey regions in the graph indicate the amount of unused capacity for each online unit at each net load level, which represents the amount of upwards flexibility each unit could provide before ramp rate constraints are included.
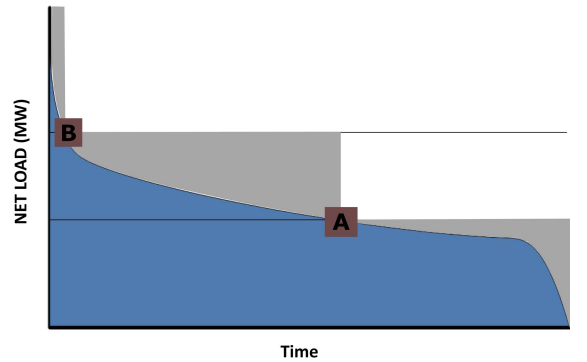

Fig. 2.   Net load duration curve

A final adjustment is required to prevent operation of units below their minimum stable output level (MSO). When a unit is scheduled to operate below its MSO, production for the next most expensive online unit is reduced by the difference between the MSO and the scheduled output of the generator on the margin. Correspondingly, the output of the generator is increased to its MSO.

D. Available flexibility

With the production schedule for each resource, Figure 2, the flexibility available from each generator can be calculated for each observation. The amount of flexibility available from an online resource is the maximum increase in power output, for a given time horizon, from that resource, limited by the difference between its rated capacity and its initial production level at each observation. This is the grey shaded area in Figure 2. Ramp rate constraints are then applied to the unused capacity for each unit. The constrained available flexibility, $F_{t,i,r}$ from online units is given by the following equation:

$$\begin{aligned} F_{t,i,r}^{Online} = Online_{t,r} * min(RR_r * i, \\ RatedCapacity_r - Production_{t,r}) \end{aligned} \tag{2}$$

where t is the observation in the NLDC, i is the time horizon, r is the index of resources, RR is the ramp rate of each unit r, and $Online$ is the boolean online variable for each resource. Flexibility can be provided from an offline state if the resource can successfully synchronize and commence production within the chosen time horizon. In the example, provided the time horizon is sufficiently long, unit 3 may provide flexibility from an online state at all net load levels below point B. The amount of flexibility available from offline resources is given by:

$$F_{t,i,r}^{Offline} = min(RR_r * (i - StartTime_r), \\ RatedCapacity_r) * (1 - Online_{t,r}) \qquad (3)$$

$$\forall i \geq StartTime_r$$

The online and offline available flexibility for each resource are added together to form the available flexibility series for a system. The flexibility available at each observation in the NLDC for the example in Figure 2 is shown in Figure 3. The only flexibility available at point A in Figure 3, corresponding to the same point in Figure 2, is from the offline units 2 and 3. Between points A and B, flexibility may be provided from unit 2, which is online, and unit 3, which is offline.
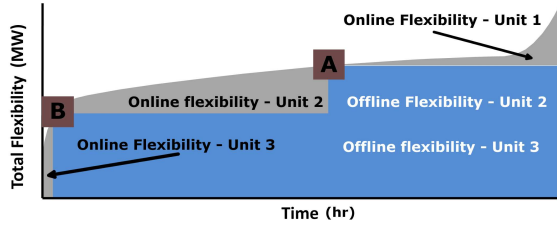

Fig. 3.   Available flexibility series

The merit order approximation of the production time series for each resource assumes that the marginal cost is the only consideration when dispatching resources. Consequently, as more expensive units tend to be smaller, merit order operation tends to maximize the amount of flexibility from online units, while fast-starting units remain offline and, depending on the time horizon studied, may provide flexibility from an offline state.

Unit commitment solutions consider many factors such as the forecast demand in the following periods and the start-up times and costs, and the ramp rates of each resource. Consequently, fast-starting, expensive resources may be dispatched out-of-merit for short periods to avoid the start-up of a large resource only required for a short period. This reduces both the online and offline flexibility available compared to merit order operation. Therefore, the merit order methodology will tend to overstate the flexibility of a system unless the production time series are altered to more closely mirror operational practice. Since non-chronological, merit order commitment minimizes system costs for each interval, the result may be sub optimal in reality. Therefore, the results of such an assessment are only indicative for initial screening applications. More detailed studies using constrained unit commitment should then be

carried out if the initial results suggest that the system may have insufficient flexibility.

In order to achieve more realistic dispatches, a hybrid merit order dispatch economic dispatch is applied. Merit order dispatch commits all units which are at maximum production below the given net load level, as demonstrated in Figure 4. The remaining net load not met by resources at full production is met by resources determined by economic dispatch. Economic dispatch will minimize the total cost of meeting the remaining load, allowing out-of-merit operation for each unit. Depending on the marginal costs of units 2 and 3 in the example system, unit 3 may be dispatched to meet the remaining net load at levels just above point A in Figure 4. Using the improved production time series, the flexibility from each unit is calculated at each point in the net load duration curve as before. The hybrid methodology produces a more realistic production time series, without significant loss of simplicity and without heavy computational burden.
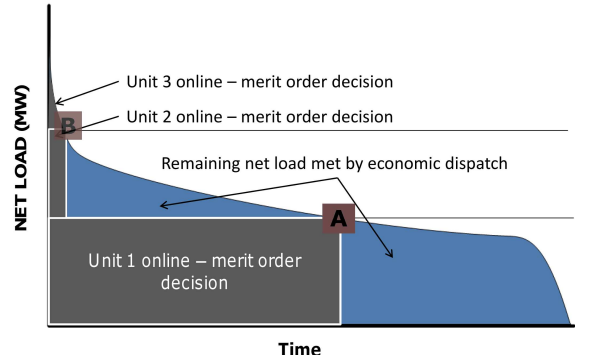

Fig. 4.   Hybrid dispatch methodology

E. Flexibility deficit

Having determined the complete series of the system's available flexibility, the ability of a system to meet upward changes in net load may be calculated. The net ramping resource deficit series, $D_{t,i}$, can be calculated by subtracting the available flexibility from the net load ramp time series, Equation 4.

$$D_{t,i} = NLR_{t,i} - (F_{t,i}^{Online} + F_{t,i}^{Offline}) \qquad (4)$$

From the net ramping resource deficit series, a number of metrics can be calculated to characterize the flexibility of a system. Positive observations in this series indicate periods when the net load ramp is larger than the flexibility available, where the number of positive observations in the net ramping resource deficit series is comparable to the IRRE outlined in [13].

In order to account for the outage of individual units, the $IRRE_{t,i}^{MERIT/HYBRID}$ is calculated again with each resource removed from the portfolio in turn. Therefore, the $IRRE_{t,i}^{MERIT/HYBRID}$ calculation for each time horizon, i, is repeated $R + 1$ times where R is the number of resources, r, in a system. When the IRRE is calculated with the loss of a resource, the overall values for the IRRE tend to be higher

for most time horizons since fewer resources are available to provide flexibility. For the three unit system here, concurrent outages of two or more resources are not considered given the low probability of occurrence. However, the methodology can be extended to include the loss of two or more resources, where the probability of such events occurring is non-negligible. The sum of the weighted IRRE values for each time horizon and with each portfolio of resources results in the final $IRRE_{t,i}^{MERIT/HYBRID}$. Each scenario is weighted by the probability of the outage event occurring divided by the sum of the probabilities of the events considered, as follows:

$$IRRE_{Final,t}^{Method} = IRRE_{Sys,t} \frac{Coeff_1}{Coeff_1 + \sum_{r=1}^{r=R} Coeff_{2,r}}$$
$$+ \sum_{r=1}^{r=R} IRRE_{\text{No unit r},t} \frac{Coeff_{2,r}}{Coeff_1 + \sum_{r=1}^{r=R} Coeff_{2,r}} \quad (5)$$

$$Coeff_1 = \prod_{r=1}^{r=R} 1 - FOR_r \quad (6)$$

$$Coeff_{2,r} = FOR_r \prod_{j=1,j\neq r}^{j=R} 1 - FOR_j \quad (7)$$

The $IRRE_{t,i}^{MERIT/HYBRID}$ can then be normalized by division of the number of upward ramps in each time horizon, for the time series studied.

Furthermore, analysis of the distribution of the magnitude of the flexibility deficits provide an insight into the sensitivity of the calculated IRRE to a change in the system's flexible resources. When the mean and standard deviation of the flexibility shortfall are small relative to the magnitude of the net load ramps, it may be inferred that a small improvement in the capability of a systems' resources, or in operational practices, may result in a greatly improved performance from the system.

Analysis of extreme deficits of ramping may highlight those rare events which are likely to pose serious threats to the system. Furthermore, by analyzing the net ramping resource deficit time series, the corresponding observations in the NLDC provide an insight into the net load levels when the system is least able to manage increasing net load, e.g. morning rise. Given the particular properties of the system, the most challenging periods may arise during times of peak net demand, or during the low net load periods, when fewer offline or online resources are available, respectively.

III. Test System

Analysis of the flexibility of an inflexible, six unit test system with 600 MW of generation capacity was carried out. Summary details of each resource in the system are shown in Table I. Furthermore, an installed capacity of 50 MW, and 100 MW, of wind power generation, with a 34% capacity factor, are also included. System demand and wind are based on the 2009 wind and load from the Republic of Ireland system. The LOLE for this system is 3.04 hours per year,

decreasing to 1.84 hours per year when 50 MW of wind power generation is included. When 100 MW of wind generation is included the LOLE is reduced further to 1.04 hours per year. The peak system demand reaches 392 MW during the winter months. The IRRE is calculated using the merit order ($IRRE_{t,i}^{MERIT}$) and hybrid ($IRRE_{t,i}^{HYBRID}$) methodologies for all time horizons between 15 minutes and 24 hour in 15 minute steps.

TABLE I
TEST SYSTEM UNIT DATA

Unit	1	2	3	4	5	6
Max. Capacity (MW)	150	150	100	75	75	50
Min. Capacity (MW)	60	50	50	40	30	10
Ramp Rate$_+$ (MW/min.)	2	2	4	4	6	10
Start-up Time (hr)	18	18	6	6	4	0.017
Forced Outage Rate	0.03	0.03	0.02	0.02	0.02	0.015
No Load Cost (€)	500	500	400	400	300	100
Marginal Cost (€)	20	20	30	30	40	50

Four principal analyses of the flexibility of the test system are available from the resulting data: the $IRRE_{t,i}^{MERIT/HYBRID}$, the distributions of net deficit and net surplus of flexibility available and the temporal distribution of the periods of insufficient ramping resources.

A. Insufficient Ramp Resource Expectation

The $IRRE_{t,i}^{MERIT/HYBRID}$ for the test system with 50 MW of wind generation is shown in Figure 5 below using both the merit order and hybrid dispatch methods presented in Section II. As anticipated, the $IRRE_{t,i}^{MERIT}$ values, given as a percentage of upward ramps, are lower for the merit order only dispatch over all time periods when compared to the $IRRE_{t,i}^{HYBRID}$ from the hybrid methodology and the $IRRE_{t,i}^{COMPLEX}$ values calculated using the detailed methodology proposed in [13], due to the additional flexibility available. Units with long start-up times (units 1 to 4) are likely to be online and units with short start-up times (units 5 & 6) may provide flexibility from an offline state. Two peak values are evident in Figure 5 at the 4 and 6 hour time horizons which correspond to the start-up times of unit, 3 & 4 and 5 respectively. For time horizons less than 4.25 hours only one unit may provide flexibility from an offline state.
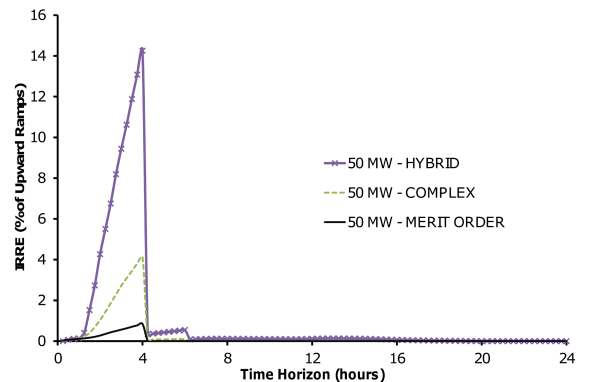

Fig. 5. IRRE calculated according to the merit order, hybrid and complex methodologies

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When compared to the $IRRE_{t,i}^{COMPLEX}$, it is seen that the IRRE resulting from the merit order dispatch underestimates the inflexibility of the system, while the hybrid method overstates the inflexibility. In reality, system operators consider the forecasted net load when dispatching units, whereas the hybrid methodology optimizes the dispatch for each period in isolation, reducing the available online flexibility. Given the conservative nature of power system reliability calculations, the IRRE using the hybrid method is considered in the following sections.

When an additional 50 MW of wind generation is included, the $IRRE_{t,i}^{HYBRID}$ and $IRRE_{t,i}^{COMPLEX}$ values are seen to increase in line with the additional net load variability associated with increased VG capacity. Figure 6 highlights the increase in the $IRRE_{t,i}^{HYBRID}$ values resulting from the hybrid dispatch, as well as the $IRRE_{t,i}^{COMPLEX}$ from the detailed unit commitment solution. While the absolute values do not coincide, the results from each method increase by similar amounts for all time periods. For example. the peak $IRRE_{t,i}^{COMPLEX}$ value at the 4 hour time horizon increases by 2%, while the peak $IRRE_{t,i}^{HYBRID}$ value at the same time horizon increases by 2.5% when the additional wind generation is added.
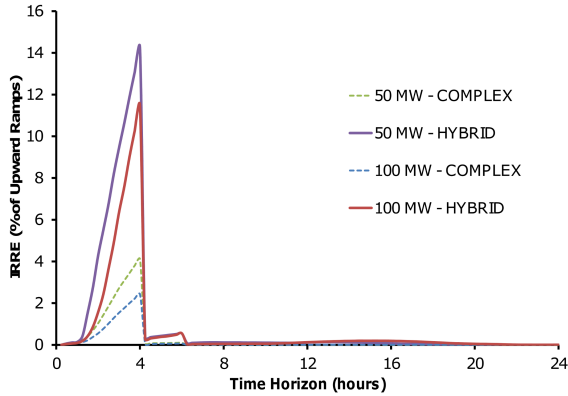

Fig. 6. IRRE with 50 MW and 100 MW of wind generation

B. Deficit of Flexibility

Analysis of those periods of insufficient flexibility, for a given portfolio and time horizon, reveals the sensitivity of the system to a potential change in the system's flexible resources. Figure 7 shows the relative frequency distribution and cumulative density function of the flexibility deficit for the 4 hour time horizon when 50 MW of wind generation is installed. The system assumes that all units are 100% reliable. The 4 hour time horizon is chosen since it indicates the peak $IRRE_{t,i}^{HYBRID}$ value, Figure 5. The distribution has a mean deficit value of 19.73 MW and a standard deviation of 11.97 MW.

Since the mean value is large relative to the size of the maximum net load ramps and the distribution is broad (standard deviation is 66% of the mean), a small increase in the flexibility of the resources or a minor change to the operation of the system will not have a large impact on the IRRE. This is commensurate with the error between the $IRRE_{t,i}^{HYBRID}$ calculated with the hybrid methodology and
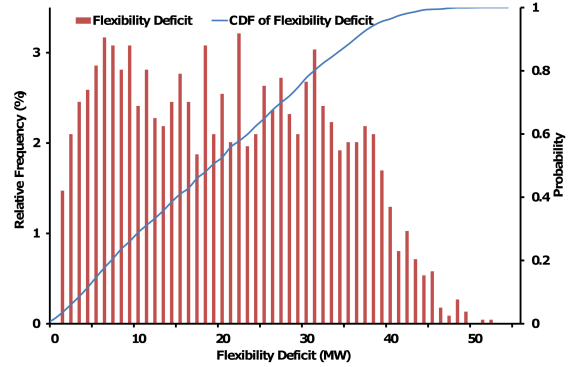

Fig. 7. Relative frequency and cumulative probability distribution of flexibility deficit

the $IRRE_{t,i}^{COMPLEX}$. Due to the potentially large error introduced by the hybrid non-chronological dispatch methodology, the system is unprepared for changes in net load, even if these can largely be forecast in reality, e.g. daily morning rise.

C. Surplus Flexibility

A similar analysis can be carried out for periods when surplus flexibility is available, Figure 8. If the average surplus flexibility is close to zero, the system may be susceptible to a shortfall of flexibility given slightly changed circumstances. While the mean flexibility surplus of 84.11 MW across 4 hour time horizons is high and the distribution is asymmetric in favor of periods with a surplus of flexibility larger than the mean, there remains 42 hours per year when there is a surplus of less than 5 MW and 272 hours when the surplus is less than 20 MW. Given the error profile evident from analysis of the flexibility deficit, this demonstrates the potential problems this system may experience, and highlights the need for more detailed $IRRE_{t,i}^{COMPLEX}$, or other, studies to be carried out.
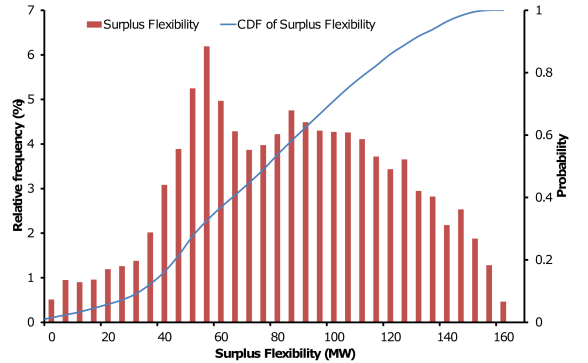

Fig. 8. Relative frequency and cumulative probability distribution of surplus flexibility

D. Temporal distribution

The net load levels at which deficits occur most frequently can also provide insight into the flexibility needs of a system. While the net load is more likely to decrease at high net load levels, it can be seen that ramps during periods of high net load do contribute to the periods of insufficient flexibility in

the 4 hour time horizon, Figure 9. More significantly, changes in net load when the net load is between 280 and 315 MW represent the majority of the number of periods of insufficient flexibility. This arises from a combination of changes in net load when unit 2 is close to maximum production, and the economic dispatch of the remaining net load when both units 1 and 2 are at maximum production.

For net load levels between 300 and 314, the least cost solution is to dispatch units 1, 2 and 6, rather than unit 3. Since unit 6 has a smaller capacity than unit 3, this has the effect of reducing the available online flexibility.
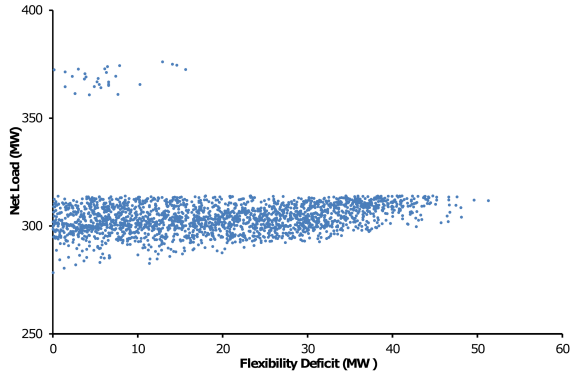

Fig. 9. Net load during periods of insufficient flexibility

Furthermore, no other units are capable of coming online in less than 4 hours, leaving no backup offline flexibility. The analysis of those net load levels contributing to the periods of insufficient flexibility can assist in determining the realism of the dispatches used in the study, and the effect of modeling assumptions on the $IRRE_{t,i}^{HYBRID}$ outcomes.

IV. DISCUSSION

The analysis methods proposed in this paper provide those involved with planning with a good insight into the flexibility needs of a system with the minimal acceptable data requirements and modeling effort. Assessment of a complicated concept such as the flexibility of a power system with high-level methods may be misleading if too much reliance is placed on the results. A large variation in the absolute values of the $IRRE_{t,i}^{MERIT/HYBRID}$ exists between both the results from the merit order only and the hybrid dispatch and the $IRRE_{t,i}^{COMPLEX}$ determined using extensive production cost simulation dispatches. The dispatch that the hybrid methodology proves implies that the flexibility available is incidental, rather than deliberately determined. A potential solution is to use the flexibility available in any given time horizon to meet upward net load ramps in shorter time horizons, i.e. decrease the net load ramp size relative to the resources available to balance the assumption that all ramps cannot be forecast.

The potential value of the $IRRE_{t,i}^{HYBRID}$ calculated using the hybrid methodology used above is that those ramping horizons which a system will have most difficulty satisfying are highlighted. Furthermore, the effect of increasing VG penetrations can be seen using the IRRE, which can then quantify the effect of proposals to meet the increased variability. The methodology presented in this paper has a distinct advantage

over simulation methodologies, since many different scenarios considering different VG production, system demand profiles, resource outages and generation profiles can be quickly carried out. This is beneficial for system planning, since the resulting portfolios can then be examined with more detailed integration planning. IRRE values may be compared between systems which have similar characteristics, enabling the comparison of the flexibility of the system in question a system which may already have successfully integrated higher levels of VG.

The distributions of flexibility deficit and surplus enable insight into the IRRE values determined and the sensitivity of the result to operational practices, transmission constraints of the system, etc. Future research will seek to characterize the sensitivity and reliability of the IRRE result to operational practices and system constraints.

The assessment methodology can be effectively demonstrated with the example system shown in section III, even though it is a small system, given the challenge the relatively few units face when meeting the changing net load. While the number of units in the system, and the number of units online are certainly factors in determining the flexibility of a system, as the size of the power system increases, the magnitude of the variability of the net load increases in tandem. Furthermore, the amount of reserve carried by a large system may be a smaller proportion of the net load than for a smaller system. This has the effect of reducing the online flexibility.

Furthermore, the example system consisted of generators exclusively, whereas many systems include other flexible resources such as interconnection, energy storage devices or DSR. The operation of pumped storage or DSR may be determined by the system operator to maximize the benefit to system operation. Therefore, it is assumed that the agreed flexibility from those resources is available at all periods.

Interconnectors can be treated as generators in the calculation of the merit order curve. The position of each interconnector in the merit order is based on an estimated cost of energy in the connecting system relative to the marginal cost of each resource in the system. The energy which is exported or required for pumping is added to the net load duration curve at the lowest net load hours. The energy required for consumption of interconnectors, storage or DSR is assumed to be equal to the energy expended by the storage facility in meeting the production schedule calculated in a first iteration (divided by the round trip efficiency of a storage resource, if applicable). The system is assumed to export over each interconnector at net load levels below the position of the interconnector in the merit order. With the updated NLDC, the production levels of each unit are recalculated.

Rules governing the operation of interconnection to other power systems are different to those for storage and DSR. Depending on the technology type, the ability of interconnection to provide flexibility differs. However, regardless of the possible ramp rates associated with those technologies, systems which are connected agree on operational limits for each interconnector. The amount of flexibility available from each interconnector is the agreed ramp rate limit for each time horizon subject to the power transfer across each interconnector (e.g. an agreement may be in place that 50

MW of reserve is always available over an interconnector in either direction).

An additional issue which certain systems may face is very low net demand levels, when inertial or other constraints prevent operators from taking conventional units offline, or a fleet of resources with long start-up times and/or high MSO levels. In this case an analysis of the downwards flexibility of a system may be useful. The methodology proposed above may be adapted to consider downwards ramping events.

While the methodology presented in this paper is significantly less complicated than the methodology used to determine the $IRRE_{t,i}^{COMPLEX}$, the are still relatively detailed for public policy purposes. Further development is required to synthesize the insight available into intuitive statements about the details of the system. If integrated into a larger qualitative and quantitative flexibility assessment tool, the hybrid methodology presented in this paper may provide critical insight into the time horizons of most concern and the effect of changes to resources or the net load, when coupled with a qualitative understanding of a given system.

V. CONCLUSION

A question asked in many systems around the world is whether market designs should reward the flexibility offered by generators. System regulators are concerned that without sufficient financial incentive, IPPs may not construct sufficient generation capacity or other resources to meet the flexibility required by the system. In reality, few system operators have accurately determined the flexibility of their existing system, making it difficult to assess the impact of a change to the resource portfolio or operational practices.

The insufficient ramp resource expectation, as determined by the methodologies presented in this paper, offers a high-level insight into the flexibility of a system. This enables further assessment of a range of portfolio options. While further analysis is required to determine the robustness of the $IRRE_{t,i}^{HYBRID}$ value proposed and $IRRE_{t,i}^{COMPLEX}$ values determined by detailed analysis, the methodology presented allows IPPs and regulators to quickly determine potentially problematic time horizons, and prepare appropriate measures to meet perceived flexibility problems, before carrying out detailed integration studies.

Furthermore, analysis of the surplus or deficit of flexibility, and analysis of net load during periods of insufficient flexibility enable an understanding of why and when a need for flexibility arises, allowing opportunities for specific measures to be readily identified to alleviate potential flexibility deficits in the future.

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