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The Role of Power System Flexibility in Generation Planning

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Abstract—As the penetration of variable renewable generation increases in power systems worldwide, planning for the effects of variability will become more important. Traditional capacity adequacy planning techniques have been supplemented with integration studies, which have been carried out in power systems with high targets for renewable generation. These have highlighted the increased variability that a system may experience in the future. As system planning techniques evolve with the demands from variable generation, the flexibility of a system to manage periods of high variability will need to be assessed. A metric may be required to measure the flexibility of a power system for use in planning studies with multi-year horizons. Compared to generation adequacy metrics, system flexibility assessment is more data intensive and requires more detailed system modeling. An algorithm for scenario development in generation planning with high penetrations of variable generation is presented.

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

I. INTRODUCTION

Generation portfolios are changing significantly in many power systems worldwide. Concern for the environment and national energy security as well as rising fuel prices have led to significant, sustained growth of wind and solar electricity generation capacity worldwide, which are set to further increase their share in many systems in the years to come. Variable generators (VG), such as: wind, solar, hydro and tidal resources, can be defined as those resources whose output is dependent on the prevailing environmental conditions. The challenge of integrating these variable resources, with limited ability to be dispatched, into existing power systems varies according to the availability of the resource, its correlation with demand and the flexibility of the power system in question. Flexibility is defined here as the ability of a system to deploy its resources to respond to changes in net load, where net load is defined as the remaining demand not served by variable generation. Hence, an isolated, inflexible power system will find it more difficult to successfully integrate

variable generation than a well interconnected, flexible power system.

A challenge faced by many power systems is to evaluate the ability of an existing system and its resources to successfully integrate variable generation and to plan future portfolios [1]. This paper will highlight the need to consider flexibility, examine the ability of current planning practices to ensure sufficient flexibility and propose adaptations of existing reliability techniques to measure flexibility.

To date, no method exists to determine the degree to which a system is flexible or inflexible in a long term planning context. At the same time as penetrations of variable generation are increasing, there is renewed interest in replacing and expanding inflexible nuclear and traditional coal generation capacity in some power systems. Foreseeing a potential deficit in fast responding resources, generator manufacturers are striving to develop more flexible generation units, with faster ramp rates and lower minimum generation levels [2]. As a result of increasing variable generation, new inflexible generation capacity and the wider development of flexible resources, assessing the ability of a system to optimally meet its flexibility requirements may become increasingly important.

This paper discusses experience with high penetrations of variable generation in Section II and current generation planning techniques in Section III. Developments in tools used in the planning of systems with high variable generation targets are explored in Section IV. Section V examines how flexibility can be assessed while Section VI identifies the role that planning for flexibility in power systems would play. Section VII concludes.

II. EXPERIENCE WITH VARIABLE GENERATION

Failure to make provisions for future flexibility requirements may lead to a system lacking the ability to respond to variability, due to load or variable generation, in a reliable manner in operational time intervals. High penetrations of instantaneous wind power have been witnessed in systems around the world, including: Denmark, Portugal and Ireland [3]. In February 2008, a large net load ramp event in the ERCOT in the USA, power system highlighted the potential threat that such ramp events pose to power system integrity [4]. While wind generation capacity may not be significant in some power systems, other variable generation technologies, such as photovoltaic or wave generation, may result in a similar requirement for flexibility in the future.

The North American Electric Reliability Cooperation's Integration of Variable Generation Task Force (IVGTF) 2008 report [1] highlighted key areas for research and development

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arising from the integration of VG. Specifically, the report of IVGTF task group 1.4 concentrated on an evaluation of the requirements for flexibility in a power system and proposed metrics by which flexibility could be measured [5]. The report drew together experience of wind and solar generation from system operators in the USA and Europe in order to identify the ramping requirements systems observe as the penetration of VG increases. Also highlighted was the role conventional generation, variable generation, demand, system operation, market structures and transmission resources play in setting the requirement for flexibility, and in providing that flexibility to the system. This is important since system operators may begin to incorporate increasing amounts of demand side resources (DSR), and allow variable generation to provide auxiliary services to a system.

The task group 1.4 report highlighted the importance of understanding three characteristics of the flexibility requirements for a power system: the magnitude of changes in net load, the time scale on which these changes occur, and the frequency of occurrence of each type of ramping event. The importance of these characteristics is to distinguish cyclical ramps, such as morning rises, from unpredictable ramps, such as 10 minute variability, as well as to match the requirements for flexibility over a given time scale with the resources available to the system to meet a net load ramp. International experience with ever increasing penetrations of VG has proven that variability may give rise to load shedding and VG curtailment [6] and that practices for dealing with variability have tended to be conservative.

III. GENERATION PLANNING

Since the construction of new transmission or generation facilities have multi-year lead times, traditional long-term planning is required to ensure the reliability of power systems in the future. Generation adequacy studies have traditionally addressed the question of how much capacity is required to reliably meet demand, at a certain time horizon. The challenge for planners is to ensure that not only is there sufficient generation capacity available to meet future demand, but that those resources can be operated in a sufficiently flexible manner. Previously, additions to an existing generation plant portfolio result from an economic optimization, based on the demand forecast, capital, fuel, operation costs and the existing generation capacity [7]. This has, heretofore, been the key driver in delivering plant portfolios which contain the necessary capacity to meet demand and to respond to changes in demand or outages of generating units.

With the development of VG in power systems and electricity market liberalization, significant uncertainty can arise in generation investment decisions. Increased risk may serve to exacerbate the problem if no party is willing to invest, resulting in insufficient capacity or unsuitable generation units being built to meet changes in net load. Identifying how much generation capacity and what characteristics that capacity should possess are key inputs for regulatory bodies, looking to ensure that market design delivers in the long run, or for vertically integrated utilities ensuring the suitability of a planned plant

portfolio before more detailed engineering and operational analyses are carried out. Investors and plant manufacturers will also have an interest in the cycling requirements experienced by potential investments.

Planning takes place on various time scales, depending on the lead time required to change or supplement a system's resources. Generation planning must start in advance of generation construction's lead time, so that effective decisions can be made concerning the addition of new resources. This task is normally carried out for long time horizons (e.g. 20 years ahead), on a rolling annual basis, by either regulators, system operators or utilities, depending on the system [8]. More detailed engineering analysis may then be carried out for the next five year horizon, to meet more immediate needs of the system. On an annual basis, maintenance schedules are planned to ensure that sufficient capacity is available to meet forecast demand, notably during peak demand periods. Closer to real time, operational planning is performed when detailed resource availabilities and more accurate demand and VG forecasts become available.

The recommendations of long-term generation planning studies are normally evaluated based on adequacy metrics, such as loss of load expectation (LOLE) [9], [10], the expected energy not served (EENS), well-being analysis [11] or peak load carrying capability (PLCC) [10], which have served industry well to date. However, metrics such as the LOLE assume that the only condition under which the demand cannot be met occurs when demand is greater than the available capacity in hierarchical level 1 (single bus network) calculations.

Long term generation planning techniques have been developed over many years. Traditional deterministic criteria, such as fixed capacity reserve levels have been complemented more recently by probabilistic methods. The deterministic criteria are based on experience of operating a power system and the likelihood of demand forecast errors or outages of generation resources. Many power systems across the world use deterministic criteria exclusively in long-term planning studies [12]. However, the planning margin can be set using deterministic metrics such as the loss of largest unit (LLU) criterion, or probabilistic methods such as an LOLE target. Well-being analysis considers both probabilistic and deterministic criteria in assessing the adequacy of a planned system's resources, and results in a set of indices which describe the system's adequacy as one of three outcomes: healthy, marginal or at risk [11]. Dragoon and Dvortsov proposed the Z-Method to measure the capacity adequacy of a power system [13], where the Z value is the ratio of the expected surplus generation at peak load hours to the standard deviation of the distribution of surplus generation at peak load hours. Previous methods make some general assumptions. The primary assumption is that load shedding will only occur during times of insufficient capacity, either generation or transmission. Secondly, in order to consider the capacity adequacy of VG, a probabilistic model is available for the output of these generators which may, or may not, be combined with a Monte Carlo simulation [10].

In systems where the ramping requirements can be forecast well in advance (i.e. with sufficient time to bring plant online), a system planner's concerns about the flexibility of a system's

resources are ameliorated but not necessarily removed. Demand forecasting has removed much of the uncertainty around ramping requirements [14] resulting in the capacity adequacy assumption that system operators can predict peak load hours, and prepare their generation resources accordingly. The power system has, in effect, been assumed able to manage all ramping in a way that avoids interruption to the demand. Consequently, the outage of generation or transmission resources and changes in the output of VG become the key drivers of remaining unpredictable ramping events.

With the development of high penetrations of VG, there is insufficient experience to heuristically determine the future ramping requirements of a system. Where a morning rise might have dominated the requirement for flexibility, the introduction of VG and DSR may alter this significantly. Additionally, forecasts of peak net load are dependent on variable generation forecasts, potentially challenging the assumption that a system operator will have enough forewarning to prepare generation resources. Hence, planning bodies have had to develop new methods to incorporate variable generation, leading to the use of integration studies.

IV. DEVELOPMENTS IN PLANNING FOR VARIABLE GENERATION

A range of tools have been developed to aid the planning of power systems where variability in the net load increases due to variable generation. Integration studies have been carried out in systems such as: California [15], the eastern United States interconnection [16] and Ireland [17], where high target penetrations for variable generation are planned. Given a lack of operational experience, these studies provide the best insight to date of how future power systems with significant penetrations of VG will be operated. These studies have tended to focus on understanding how VG will impact on the daily operation of a power system by employing production cost models.

Unit commitment and economic dispatch models use forecasted load and variable generation, and typically investigate year long, or multi-year simulation of the operation of a power system. The adaptation of unit commitment to a stochastic [18] and rolling framework, and the inclusion of VG forecasts [19] can provide an insight into how systems might operate in future at high VG penetrations. Finally, traditional reserve constraints have been enhanced to provide additional reserve for VG forecast uncertainty [16], [17].

Flexibility has been provided in these integration studies by altering the traditional reserve constraints in production cost studies [16], [17]. In order to reach their respective targets, additional flexibility has been required through either the provision of increased reserve, the construction of transmission, or alternative market design or operational procedures.

Operating reserve, the reserve available to system operators in the event of a resource outage or an unpredicted variable generation ramping [20] is typically planned for on a day ahead basis, to ensure that the planned quantities of reserve match the generation resources available. In many systems the amount of reserve required has been determined by the loss

of the largest unit or a similar deterministic criterion. Current practice favors probabilistic methods [21] over traditional deterministic methods [22], which try to calculate the "right" amount of operating reserve for a power system.

Driven by the use of integration studies, much effort has recently been dedicated to identify the reserve requirements for VG. Soder [23], Dany [24], and more recently, Doherty [25] and Morales [26] have developed probabilistic methodologies to determine the optimal amount of operating reserve required when wind generation is included. The methods proposed by Doherty [25] and Morales [26] focus on a daily evaluation of the operating reserve requirements based on the statistical properties of wind and demand forecasts, as well as the outage probabilities of each generation resource. Subsequently, the required quantities for the existing reserve categories are adjusted in order to account for the VG. Consequently, the flexibility of a generation portfolio is a function of the operating reserve algorithm employed.

Integration studies require extensive data, effort and computation to produce indicative results of future power system operation and are dependent on a proposed generation portfolio, which is in turn dependent on capacity adequacy studies. Therefore, portfolio development is an iterative process in order to ensure the optimum generation portfolio at least cost. A number of integration studies and reports have highlighted the need to assess and provide flexibility as VG is integrated over time [1], [16], [27].

V. FLEXIBILITY METRICS

Key tasks for long term planning currently include demand forecasting, VG forecasting, establishing planned resource closures and construction, capacity expansion studies and adequacy calculations. Planning for the successful operation of a system has traditionally been left to generation investors and system operators to resolve since the flexibility of a system is a function of not only the generation resources but also the manner in which they are deployed.

Table I categorizes elements of a power system as either a flexibility sink, a flexible resource or as an intermediary. Different system characteristics alter the requirement for flexibility such as: the variability of the demand and VG profiles, the predictability of VG power output, the temporal correlation of VG with system demand, the geographical and technological spread of the installed variable generation, and the capacity of installed VG relative to the peak demand in a system. Consequently, an assessment of a system's flexibility should consider all of these characteristics and their relationships within the system.

Dispatchable generation, interconnection, DSR and electricity storage provide the physical ramping required by a system. Flexible resources can be categorized as either uni-directional or bi-directional. Uni-directional resources are those which can only generate power while bi-directional resources can both absorb and generate power (e.g. interconnectors and electricity storage).

As previously mentioned, the ramping requirements will differ over the time interval chosen [28]. A distinction exists

TABLE I
CHARACTERIZING THE FLEXIBILITY OF POWER SYSTEM ELEMENTS

Resources	Intermediary	Sink
Conventional generation	Transmission network	Load
Dispatchable VG	Fuel storage	Wind
Interconnection	Forecasting	Solar
Electricity storage	Market design	Ocean
Demand-side measures	Regulations	
	Balancing area size	
	Unit commitment	

between frequently required small amounts of flexibility over short time periods, and more infrequent large amounts of flexibility over extended periods. The frequency of occurrence of the required flexibility as a function of the duration and magnitude of net load ramps is shown for the Republic of Ireland system in 2009 in Figure 1 below.

Fig. 1. Frequency of required flexibility as a function of ramp magnitude and time interval.

Figure 1(a) illustrates the small but frequent changes in net load for small time intervals as expected, while Figure 1(c) highlights the infrequent, yet large, changes in net load production for time intervals greater than two hours. The distinction between the types of flexibility required is important, since different flexible resources are available over different time intervals, due to their physical characteristics and longer duration, larger magnitude changes can be forecast with greater predictability.

Some resources can provide large amounts of ramping capacity over several hours, e.g. coal-fired plant, but cannot provide much ramping capacity in intra-hour time intervals. Smaller, fast acting resources can provide a higher share of the system flexibility in intra-hour intervals, but a smaller share over longer intervals. As a result, it is important that flexibility is considered over different time intervals at the planning stage.

Furthermore, only generation units which are online, storage units with pumping capability, and certain demand side resources can provide flexibility when net load is decreasing, while online units, or resources which can start up within the specified time interval can provide the flexibility required when net load is increasing. Therefore, upwards and downwards flexibility must be assessed separately since both are a threat to system reliability and are managed using different pools of resources. Assessment of flexibility considers not only the generation capacity, but also the effect that energy storage

facilities, demand side resources (DSR), interconnection and the effect of unit commitment and market rules exert on the flexibility of a power system.

While the requirement for flexibility can be calculated using only the net load time series, the availability of resources to provide flexibility requires data about the availability and production levels of each resource which provides flexibility in order to correctly model the impact that operational practices have on the provision of flexibility in a system.

In contrast to the forced outages of generators, generators' production levels are not independent random variables, since the system operator imposes production levels depending on a resource's bidding strategy. The production levels of generators with similar bids will tend to be highly correlated, as will those whose output is dependent on an environmental condition, such as rainfall.

As a result, the availability of each resource to provide flexibility will be correlated to units with similar characteristics. Since many systems are composed of significant blocks of generation capacity of the same technology (e.g. CCGTs from the same era), assuming independent resource behavior may significantly overestimate the flexibility of a power system.

A planning metric to measure the flexibility of a system, in the same way as the LOLE measures the capacity adequacy of a power system, would be desirable. Given a dearth of experience of operating power systems at high penetrations of variable generation, a degree of certainty is sought in the planning process that a system will be able to withstand planned increases in VG penetration. Bearing in mind the issues surrounding the measurement of flexibility mentioned previously, such a metric should try to achieve the following aims:

- 1) Quantify the ability of a system to respond to short-term changes in demand, VG, and generation unit outages in a long-term planning context.
- 2) Minimize data requirements and computational effort, while appropriately considering the operational constraints of a system.
- 3) Remain independent of existing operating policies to ensure portability between power systems.

Any proposed metric should complement capacity adequacy calculations and system operation simulation at the planning stage. The use of such a metric would ensure that planned systems meet the objectives of possessing both sufficient capacity to meet demand, and sufficient ability to meet changes in net load.

VI. LONG TERM PLANNING FOR FLEXIBILITY

The introduction of VG has necessitated a change in the manner in which power systems are planned. Integration studies have added a stage of detailed modeling to the planning process, while a flexibility assessment requires a new paradigm for generation planning. Here we propose an approach which integrates existing planning techniques with the assessment of flexibility, Figure 2.

The overarching principle proposed here is that generation planning should commence with the least data intensive steps

Fig. 2. Generation planning scenario development algorithm

and progress to the most data intensive steps in an iterative process. By commencing with a traditional capacity adequacy calculation, such as the LOLE, an initial generation portfolio can be developed which meets the adequacy standards for the system. Since the evaluation of system flexibility is more data intensive, this is the next stage in the process. This is carried out for all time intervals desired and in both directions. Should the unit commitment model used to calculate the flexibility of a system contain the same unit commitment and economic dispatch model as the production cost model, the two steps can be combined. This hierarchy of assessment reflects the aims of the planning process: to provide a reliable, operable, least cost generation portfolio for the given study period. If excessive or inadequate flexibility is observed, the generation portfolio or unit commitment model can be altered to meet the dual aim of minimizing cost and meeting a specified flexibility standard.

There are no current methods of assessing the flexibility of a system in a planning context. However, da Silva et al. [29] attempt to measure flexibility by approach the operating reserve problem from a planning point of view, employing sequential Monte Carlo simulations of demand, wind output, and hydro capacities, combined with unit commitment and economic dispatch, to evaluate a range of reliability metrics for a system. Various options for capacity addition can be evaluated using this method to ensure that additional resources meet both the capacity adequacy and operating reserve needs of a system. This method is restricted to generation outages, and demand and VG forecast errors, rather than identifying how well a system can cope with the overall variability of the net load.

Organizations such as the North American Electric Reliability Cooperation (NERC) [5], [30] and the International Energy Agency (IEA) [31] have undertaken studies to develop planning aids to understand the required operational procedures with high penetrations of VG from a long-term viewpoint. A metric in the inception stage is the insufficient ramping resource expectation (IRRE) [30] which attempts to quantify

flexibility using similar principles to the LOLE. While the approach outlined in [30] is a nascent idea, it does provide the first explicit attempt to calculate system flexibility. The IRRE seeks to statistically model a system's available flexible resources for each time interval and in each direction. This is then compared to the demands for flexibility and a statistical estimated value for the number of periods during the year when the system is unable to provide the required flexibility.

In its current state the IRRE requires that a planner carry out a unit commitment and economic dispatch for the proposed system for the study year. With details of the production of individual generators over the net load time series, a resource model is constructed by calculating the flexibility available in the system at each instance in time and from that creating the cumulative density function for the available flexibility in the system during the year. Then assuming that changes in net load are independent of the available flexibility distribution, the probability of each ramp in each time interval can be calculated, from which the expected value of periods when the system cannot meet the system's needs is derived.

VII. CONCLUSION

As the penetration of variable generation increases in power systems worldwide, the calculation of flexibility in a planning context may be required. The development of integration studies and new techniques to evaluate the operating reserve required by VG testify to the need for new planning tools. The assessment of system flexibility is the next step in the evolution of generation adequacy planning tools.

However, any proposed flexibility metric will be more computationally intensive than traditional metrics, such as the loss of load expectation, since the flexibility requirement differs over longer time intervals, in each direction of ramping, and is a function of how the system is operated. Additionally, the resource pool available to the planner and operator to manage net load ramping is wider (e.g. DSR) since an increased variety of technologies may be employed. New metrics will be required to model the contribution that flexible resources make to system reliability, arising from net load ramps.

Future work in this area should be concentrated on: identifying the requirements for flexibility, developing metrics for flexibility further, understanding the impact of operational tools, such as forecasting and unit commitment, on the outcomes of long term planning metrics. Investigation of the dependence structures between the availability of flexible resources would be of great value, since this would negate the need for repeated use of unit commitment tools in the planning process.

Flexibility metrics will be needed to assess the relative merits of making an operational policy change, such as reserve target calculations; evaluating the addition of competing generation technologies, or unit commitment types; and the impact of pooling balancing areas together. As the penetration of variable generation increases, an explicit understanding of effect of changes to a system's flexible resources may become essential in order to maintain a reliable system.

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