

Integration of Variable Generation: Capacity Value and Evaluation of Flexibility

Eamonn Lannoye, *Student Member, IEEE*, Michael Milligan, *Member, IEEE*, John Adams, *Member IEEE*, Aidan Tuohy, *Member, IEEE*, Hugo Chandler, Damian Flynn, *Member, IEEE* and Mark O'Malley, *Fellow, IEEE*

Abstract—As integration of variable generation continues to grow rapidly in power systems globally, system planners are seeking new tools to understand the role of variable output generators and the challenges experienced with their integration. The North American Electric Reliability Corporation (NERC) has established a task force to examine the integration of variable generation. This paper details the achievements to date and outlines ongoing efforts from Task 1.2 on the capacity value of variable generation and from Task 1.4 on the concept of flexibility in power systems and options for its definition. Arising from international collaboration with the International Energy Agency, a discussion on the definition of flexible resources is presented. A potential metric for flexibility offered by conventional plant is developed and applied to a test system.

Index Terms—Power System Planning, Power System Reserves, Variable Generation Integration, Power Systems

I. NOMENCLATURE

CCGT	Combined Cycle Gas Turbine
DSR	Demand Side Resource
ELCC	Effective Load Carrying Capability
ERC	Effective Ramping Capability
EUE	Expected Unserved Energy
IEA	International Energy Agency
GIVAR	Grid Integration of Variable Resources
IRRP	Insufficient Ramping Resource Probability
IVGTF	Integrating Variable Generation Task Force
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
NERC	North American Electric Reliability Corporation
RAR	Ramping Availability Rate
VG	Variable Generation

II. INTRODUCTION

TO date, North American experience with variable generation has been limited to integration of a relatively small amount of the total generation within a power system or balancing area (i.e. typically less than 10%).

The industry is now starting to realize the potential for operational reliability issues, though typically the integration of variable generation has not appreciably affected the reliability of the bulk power system. Anticipating substantial growth of variable generation, NERC's Planning and Operating Committees created the Integration of Variable Generation Task Force (IVGTF) who prepared a report, entitled, "Accommodating High Levels of Variable Generation," [1] which was released in April 2009.

In addition to defining various technical considerations for integrating high levels of VG, the report identified a work plan consisting of twelve follow-on tasks to investigate potential mitigating actions, practices and requirements needed to ensure bulk system reliability. These tasks were grouped into the following four working groups with three tasks each:

1. Probabilistic Techniques
2. Planning
3. Interconnection
4. Operations

The rate of integration of large amounts of these variable resources is accelerating due to decreasing costs, energy policy and assistance from national fiscal stimulus packages [2]. The availability of a variable resource is dependent on environmental factors such as the wind, tidal forces or sunlight. Environmental drivers can change frequently, causing variability and uncertainty in output levels so that the seasonality and volatility of variable generators add a new dimension to the problem of meeting demand.

Many system operators have carried out integration studies to detail the feasibility of including variable resources and to determine the specific challenges that will be involved [3,4,5]. The scale and extent of the change in the requirements for system operation and planning are becoming apparent through these studies.

Key outcomes from the task force report included recommendations to explore diversity, both geographical and technical, in variable generators; the effect of forecasting; the availability of flexible resources such as storage, demand response and electric vehicles; transmission expansion and reinforcement and new approaches to planning. These issues were allocated to

E. Lannoye (eamonn.lannoye@ucd.ie), A. Tuohy (aidan.tuohy@ucd.ie), D. Flynn (damian.flynn@ucd.ie) and M.J. O'Malley (mark.omalley@ucd.ie) are with the Electricity Research Centre, University College Dublin, Dublin, Ireland. M. Milligan (michael_milligan@nrel.gov) is with the National Renewable Energy Laboratory, Golden, CO. J. Adams (jadams@nyiso.com) is with the New York Independent System Operator, Schenectady, NY. Hugo Chandler (hugo.chandler@iea.org) is with the

various task groups, the details of which can be found in [1]. This paper will focus on the outcomes of Task 1.2 and 1.4, which are presented together due to the commonality of purpose between the groups.

Section III will describe the work undertaken by Task 1.2 towards a capacity value calculation for variable resources. The group has established the effective load carrying capability (ELCC) as the prime method of capacity value calculation for variable resources. Flexibility has not previously featured predominantly in power system planning, since meeting demand economically was the single key factor. The IEA Grid Integration of Variable Resources group has begun a process to define flexibility in the context of high penetrations of variable generation and to examine sources of flexibility. Section IV discusses some of the conclusions drawn as a result of this process.

Task 1.4 is directly concerned with building an understanding of system requirements for flexibility, current usage of flexible resources and the development of flexibility metrics. Findings from this process are presented in Section V. Section VI describes a possible method to evaluate the flexibility offered by conventional plant, based on the ELCC method used in Task 1.2. Section VII concludes.

III. VARIABLE GENERATION CAPACITY VALUE: TASK 1.2

Task 1.2 is concerned with developing a consistent and accurate method (or possibly methods) to calculate the capacity value attributable to variable generation (VG). The objective of the task is to produce a report that investigates approaches for calculating the contribution of VG, and discusses data requirements.

At the time of writing, the Task 1.2 Working Group (T1.2) report is in progress. We anticipate completion of the report before the IEEE PES Summer Meeting, with results reported at the panel session.

T1.2 has identified the ELCC metric as the most promising approach. ELCC can be based on LOLP, LOLE, EUE, or related reliability metrics. The principle behind ELCC is that the risk of a loss of load (or need to import) event is maintained constant with and without VG. Therefore, ELCC measures the increase in load that can be served at the same level of reliability after adding VG into the generation mix.

T1.2 also identified data availability as a key issue that must be addressed. LOLP calculations depend upon accurate forced outage rate data from conventional generators. Typically these are based on the long-term performance for power plants of a given size range and type. In order to ensure that the ELCC calculations for VG are on an equivalent basis, long-term data from the VG is required. In addition, since wind and solar generation are a function of the weather, it is essential that all VG data is synchronized with each other and with the load data for the study in question. Asynchronous data introduces inconsistent weather drivers for the load

and VG, resulting in potentially misleading conclusions. This issue is identified in [6,7]

Several of the recent wind integration studies in the United States have calculated wind ELCC over a 3-year period. A recent study in Ireland [8] shows that a 4-year data series will produce an ELCC that is within 10% of the long-term value. Additional application of this method in other parts of the world will indicate whether this is a robust result.

Another aspect of the T1.2 work is to survey North American entities and compile a listing of approaches that are used today to calculate VG capacity value. Some entities use ELCC, but others use approximation methods that are less computationally expensive. One common approach is to calculate the capacity factor of the VG over a suitably-defined peak period. As shown by Milligan and Parsons [9] the capacity credit of the wind power over the peak load hours can approximate the wind capacity value reasonably well. This has been corroborated by other studies [6]

The panel presentation will show

- IVGTF report highlights and recommendations
- Current practice of calculating wind and solar capacity value in North America
- A comparison of NERC recommendations with those of the IEEE Wind Power Coordinating Committee's Wind Capacity Value Task Force

IV. FLEXIBILITY IN POWER SYSTEMS

The IEA GIVAR project aims to establish a flexibility assessment method that will enable broad assumptions to be made about the flexibility of power areas, and thus their potential for VG share, on the basis of certain fundamental characteristics. The term "power area" is used, instead of power system, as the GIVAR project also examines areas which are part of a larger power system and, conversely, areas consisting of several power systems.

As the share of variable generation increases in power systems, system operators will be faced with the challenge of how best to operate their system to cope with the increased variability. The key is system flexibility, which comes in the form of both flexible resources and institutional flexibility. Already, power systems must be sufficiently flexible to deal with variable load profiles, so low shares of VG can be integrated with minimal effort. As the share of VG on the system increases, the flexible resource will, firstly, have to be optimally used, and then extended with new flexible resource capacity.

Flexible resources are considered here to be flexible conventional plant (e.g. open cycle gas turbines), storage, demand side resources (DSR) and internal and external transmission. Transmission is considered a resource here as it enables flexible resource to be shared between areas,

and VG to be transmitted across larger areas. These resources can all essentially perform the same function when it comes to balancing variability, i.e. they provide active power (MW) to balance the variation in both VG and load. However, the way in which they each provide this is different and needs to be considered for each resource.

Conventional plants are easiest to understand – they provide active power and are generally not limited in how they do this, i.e. magnitude and duration, except by ramping rates. Storage is similar, but it will have a capacity (MWh) limit which may reduce its usefulness. However, an additional benefit of storage is the ability to reduce curtailment by increasing demand – this can also be offered by DSR and connection to other systems, if the system characteristics are suitable. DSR is the least utilized form of flexible resource at present – with the development of the ‘smart grid’ this should become a more widespread resource, as customers participate actively in the market, either by themselves or aggregated. However, in general, today’s wholesale markets do not stimulate participation in DSR, and would therefore need to be redesigned somewhat to achieve these aims. It is likely that DSR could be available either to curtail demand (i.e. a consumer will reduce demand when the price rises above a certain level) or shift demand (i.e. moving load from a time of higher prices to a time of lower prices). As well as responding to price however, the DSR could also be directly used to assist the integration of VG, since with a large enough VG share, times of high generation should correspond to low prices. The final resource considered is improved connection between systems, since if systems are well interconnected, resources can be shared, as well as smoothing the overall variability seen by the combined system.

These flexible resources, if present, need to be well utilized since capital costs for flexible plant tend to be high. This will require a number of institutional measures. Foremost among these is the design and operation of the market. Markets designed to better integrate VG will, among other things, have shorter gate closure, make good use of advanced forecasting and scheduling techniques, be well coordinated with neighboring markets and value flexibility (i.e. provide a good return for those resources which are mainly used for providing balancing power to variable resources). Forecasting and unit commitment issues are currently being explored by Task 2.1. If a market is well designed, it will allow higher shares of VG to be integrated. Other institutional characteristics that should enable greater use of VG include the size of the area (bigger areas will mean smoother, less variable outputs), a technological spread (a mix of solar PV and wind should be less variable than wind alone), a large existing need for flexibility (i.e. those systems with strongly variable demand will be better equipped to deal with VG) and those with diurnal

or seasonal characteristics for demand which are similar to the VG resource (i.e. if wind output is highest during a winter day and demand is at its peak at the same time).

By combining the available flexible resources, taking into account institutional practices that either help or limit the use of this resource, and recognizing the existing need for flexibility, the available flexibility to integrate VG resources can be quantified, giving an indication of the share of renewable generation that may be achievable, without a change in existing practices.

V. FLEXIBILITY IN POWER SYSTEMS: TASK 1.4

Task 1.4 is focusing on how resource adequacy and transmission planning approaches will need to consider system flexibility in order to accommodate the characteristics of variable resources as part of bulk power system design. In the past, resource flexibility has only been considered from the perspective of overall plant availability in planning studies, as measured by such metrics as effective forced outage rate (EFOR), which is translated into LOLE, LOLP, reserve margin, etc.

Historically, planning studies have not generally needed to concern themselves with some level of quick response resources in order to respond to a large resources base, which would be considerably more variable in real-time operations as compared to today’s resource base. In the past with the characteristics and performance of conventional generating technologies well understood, power system variability was addressed in resource planning studies by identifying the most economic resource mix to meet a time varying load profile and in transmission planning studies by evaluating loss of source in the local area.

However, as noted in the IVGTF report [1], high penetrations of variable generation will result in a significant increase in the overall system variability whether measured from the net-load (load - variable generation output) or resource perspective. The question then becomes; what changes will be required in planning studies to account for this increase in system variability and how can it be measured?

Task force 1.4 has begun its work and has developed a study approach that will; i) document the experience of power systems that already have a relatively high penetration of variable generation; ii) describe the characteristics of variable generation and their interaction with the load; iii) identify sources of flexibility such as load following capability, regulating reserves, contingency reserves, quick start capability, storage, flexible demand, operational practices such as shorter scheduling intervals, etc. This information will be utilized to assess if and how flexibility is currently accounted for in existing studies, how flexibility can be modeled in planning studies and what kind of metrics will be needed to measure flexibility in planning studies.

VI. EVALUATION OF FLEXIBILITY IN CONVENTIONAL PLANT

One possible method for quantifying the existing flexibility in power systems is by calculating an Effective Ramping Capability (ERC) available to the system operator from conventional plant. This method is based on the Effective Load Carrying Capability tool that is used in Task 1.2 to determine the capacity value of VG [10]. While the ELCC approximates a unit's contribution to meeting overall demand, the ERC attempts to approximate a unit's contribution to meeting net load changes. The ERC is a planning metric comprised of a set of values, describing a unit's contribution to the system's ability to ramp in a given direction over different time scales. Time steps can be chosen to match the data which exists for a system or to the time steps used in reserve categories, such as 10 and 30 minutes. For example, the ERC_{15}^+ is the additional active power a unit contributes to the system in 15 minutes, while the ERC_{60}^- is the decrease in unit output in 60 minutes.

The ERC calculation is substantially the same as the ELCC calculation, except that rather than using the maximum rated output for the unit, the unit's maximum ramp in a given direction, for a particular time period is applied. This is a function of the minimum and maximum generator output levels and the maximum unit ramp rate. The forced outage rate is replaced with a new set of variables named the Ramping Availability Rate (RAR).

The RAR represents the fraction of time that the unit is both online, or can become operational, and available to offer the maximum ramp in a given time period. It is constrained to a range of 0 to 1, where 0 indicates no availability to ramp and 1 indicates a unit which is always available to ramp. The time period and the direction of the RAR matches that of the desired ERC calculation (e.g. up ramp, down ramp, 15 min, 60 min, 240 min, etc.). The RAR indicates the probability that a unit will be able to deliver its maximum ramp at any time. The RAR is determined from historical dispatch data or through graphical analysis of a unit's power duration curve. Peaking and flexible plant will tend to have higher RAR values, due to the high proportion of time when the units are at minimum operating levels or are idle. In contrast, coal and nuclear units will tend towards lower RAR values due to the high proportion of time when the unit is at maximum rated output.

A system operating characteristic is created of a unit's ramping resource, taking into account the forced outage rate and the RAR, which is equivalent to the Capacity Outage Probability Table in ELCC studies. The convolution of the positive, and separately the negative, changes in net load with the ramp resource distributions of the system leads to the Inadequate Ramping Resource Probability (IRRP), which is equivalent to the Loss of Load Probability (LOLP) in ELCC studies. The target value for this probability can be adjusted to the desired reliability level. The ERC calculates the maximum ramping capability of the system *without* the generator in question with respect to the desired IRRP target. A second iteration is performed *including* the selected unit

and a new ERC is found for the same IRRP – this will lead to an increased ERC for the system. The difference between the two results provides the Effective Ramping Capability for the unit. A comparison of terminologies is shown in Fig. 1.

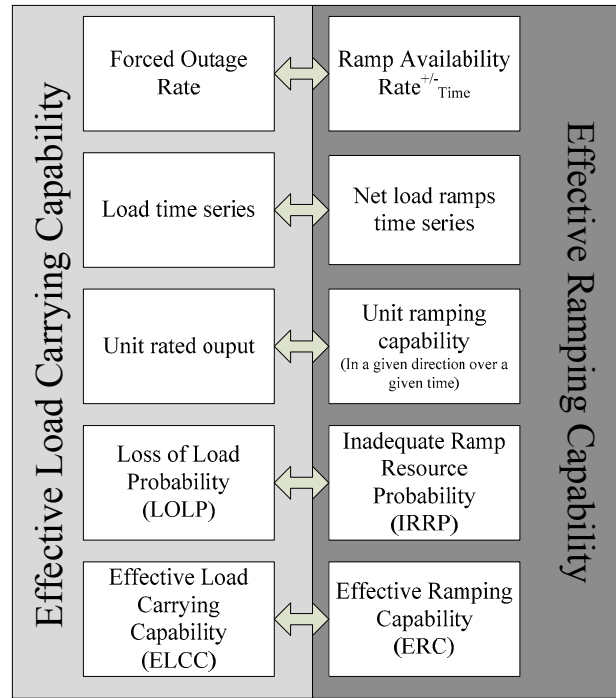


Fig. 1 Terminology for ELCC and ERC methods

A. Validation

This method has been tested on a conventional thermal and hydro plant test system, consisting of 30 units and using 15 minute resolution wind and load data for 2008 [11]. The Ramp Availability Rates over a 15 minute time scale are calculated from each unit's historical operation. Ranges for positive RAR values for each unit type are shown in Table I. A unit's ERC is calculated from the difference between the system ERC before and after the inclusion of that unit, with respect to a constant IRRP.

Figure 2 demonstrates how the ERC_{15}^+ for units of varying rated ramp rates are dependent on the RAR_{15}^+ . Based on the RAR values from Table 1, the RAR_{15}^+ would be in the region of 0.09 to 0.12 for base loaded units such as CCGTs and coal plants, and 0.85 to 0.99 for peaking and hydro pumped storage units. Peaking units have higher RAR_{15}^+ values, due to the amount of time such units spend at idle, operating at minimum output and low startup times.

Table I
15 minute positive Ramp Availability Rates

Type of Unit	Ramp Availability Rate ⁺ ₁₅
Peaking Units, Pumped Storage	0.92 – 0.99
High / Mid Merit Gas and Oil	0.8 – 0.95
Base-load Gas CCGT	0.09 – 0.1
Base-load Coal and Peat	0.1 – 0.12

For these RAR_{15}^+ values the ERC_{15}^+ for a 300 MW CCGT with a 15 minute positive ramp of 75 MW, the

unit can reliably be depended on to provide a positive ramp of 3.66 MW over 15 minutes. This is significantly less than the rated ramp, indicating that the unit is operated in a manner which reduces its availability to provide a ramping resource. A pumped storage unit with the same ramp rate over 15 minutes but with an RAR_{15}^+ of 0.99, will result in an ERC_{15}^+ of 73.09 MW. This unit is a greater system asset in a ramping context than the CCGT, even though they offer the same rated ramping capability. A smaller RAR_{15}^+ for the CCGT and the larger size of the unit reduce the ERC_{15}^+ .

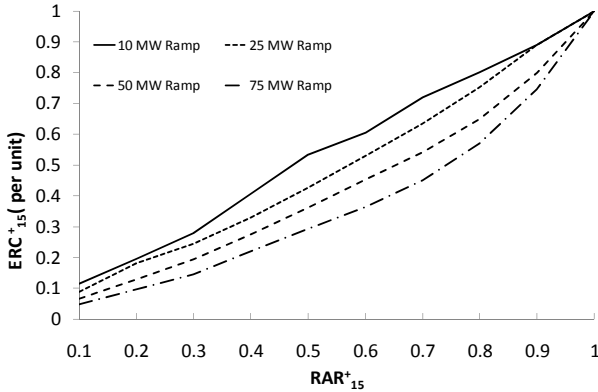


Fig. 2 Positive Effective Ramp Capability for four sample units in the test system as a function of the Ramping Availability Rate.

As demonstrated in Figure 2, the ERC_{15}^+ for each unit increases as its availability to ramp increases. The size of the unit will affect the ERC of that unit. A smaller peaking unit, such as an OCGT, with a positive rated ramp of 10 MW but with the same RAR_{15}^+ as the pumped storage device will have a higher per unit ERC_{15}^+ since the loss of the OCGT will have less of an impact on the system's ability to meet ramping events. Figure 3 shows the ERC_{15}^+ as a function of unit size for two sample RAR_{15}^+ values. The per unit value of the ERC_{15}^+ decreases as the unit size increases due to the impact on the system of the loss of a large ramping unit. The peaks in the per unit ERC_{15}^+ function at lower values might indicate an efficient design and operation point for units when providing ramping.

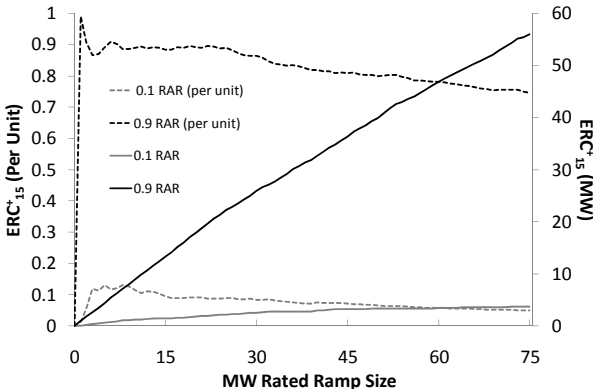


Fig. 3 ERC_{15}^+ and per unit ERC_{15}^+ as a function of unit size.

Estimating the set of ERC values for each unit in a system approximates the system's ability to cope with variability for a given degree of reliability. Similar to the

ELCC method for generation adequacy, the system operator can plan for a system variability adequacy. The sum of all units' ERC should be greater than the forecast or benchmark ramp expected in a time step. A system experiencing 500 MW positive ramps in 15 minutes will require in access of that amount due to the probabilistic method used to evaluate the resource.

This method has some restrictions. Current operational practices are likely to change as variable generation penetration increases. Since the RAR values approximate the operational characteristics of a unit, estimating RAR values at high penetrations involves an understanding of how the system will be operated in the future. Over shorter periods, these changes are incremental allowing the RAR to be estimated with greater accuracy. Over the longer term, economic incentive may lead to improvements in unit performance so that physical characteristics are the limiting factor.

The panel presentation will:

- Present methods for the calculation of flexibility metrics such as the ERC and others resulting from Task 1.4
- Show applications of these methods in planning tools.
- Present results for individual units in the test system.
- Discuss the advantages and disadvantages of each method and highlight their limitations.
- Highlight further developments necessary.

VII. CONCLUSION

This paper has detailed the ongoing effort by the NERC IVGTF partners to resolve some of the key issues in the integration of variable generation into power systems. Arising from the recommendations of the IVGTF report [1] Tasks 1.2 and 1.4 have examined two of the major issues.

Task 1.2 has examined methods to reliably calculate the capacity credit of wind generation. Power system operators were surveyed to establish what methods they are currently in use to evaluate the capacity credit for wind and the level of their complexity. The group also examined the amount of data necessary for accurate determination of the capacity value of wind.

The issue of flexibility in power systems has been examined by Task 1.4 and by members of the IEA. These outlined resources available to the system to operate with a higher degree of flexibility. Experiences of system operation with high penetrations of VG were collected in order to gain an understanding of how operations might change for other power systems in the longer term. An understanding of how each type of flexible resource interacts with the balancing operation carried out by system operators has been developed, identifying possible solutions for systems with specific flexibility related problems. Also examined was the degree to which flexibility was an issue in generation planning and how it has been accounted for.

In order to plan for power systems to be operable with high penetrations of VG, one possible metric was developed based on the ELCC metric for generation adequacy. The ERC measures a conventional unit's contribution to the system's ability to ramp in either direction over varying timescales, mimicking the ELCC calculation for calculating a unit's contribution to meeting demand. The ERC provides a simple and computationally inexpensive method to determine the flexibility offered by conventional plant.

VIII. ACKNOWLEDGMENTS

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X. BIOGRAPHIES

Eamonn Lannoye (S'08) received the B.E (Hons.) degree in mechanical engineering from University College Dublin, Dublin, Ireland in 2009. He joined the Electricity Research Centre in UCD as an Irish Research Council for Science, Engineering and Technology Embark Initiative doctoral student. His research is concerned with flexibility in power systems with high penetrations of variable generation. He is a student member of the IEEE Power and Energy Society.

Michael R. Milligan (M'98) received the B.A. degree from Albion College, Albion, MI, and the M.A. and Ph.D. degrees from the University of Colorado, Boulder. He is a consultant for the National Renewable Energy Laboratory (NREL), National Wind Technology Center (NWTTC), in Golden, CO. He works on ancillary service impacts and system reliability and other issues related to planning and operation of systems with wind. Before coming to NREL in 1992, he worked for several years in power systems planning. He is a member of the Department of Energy's Wind Powering America team. Dr. Milligan is leader of IVGTF Task 1.2 and a member of the IEEE Power and Energy Society.

John Adams (M '78) is the Principal Electric System Planner with the New York Independent System Operator (NYISO), Schenectady, NY. He is chairperson of IVGTF Task 1.4

Aidan Tuohy (S'05) received the B.E. degree in electrical and electronic engineering from University College Cork, Cork, Ireland, in 2005 and the Ph.D. degree from the Electricity Research Centre, University College Dublin, Dublin, Ireland in 2009. His research interests are in the integration of wind energy in power systems.

Hugo Chandler is an analyst in the Renewable Energy Division of the International Energy Agency, where he is responsible for wind energy issues and the Grid Integration of Variable Renewables project. Previously he worked for the wind industry in Brussels. Mr. Chandler has an M.Sc. in energy technology and policy from Imperial College London.

Damian Flynn (M'96) is a senior lecturer in power engineering at University College Dublin. His research interests involve an investigation of the effects of embedded generation sources, especially renewables, on the operation of power systems. He is also interested in advanced modeling and control techniques applied to power plant. He is a member of the IEEE.

Mark O'Malley (F'07) received B.E. and Ph. D. degrees from University College Dublin in 1983 and 1987, respectively. He is the professor of Electrical Engineering in University College Dublin and is director of the Electricity Research Centre with research interests in power systems, grid integration of renewable energy, control theory and biomedical engineering. He is member of the Power and Energy Society and a fellow of the IEEE.