Authored by: Si.Gillett@humbeat.co.uk

Power system fundamentals

This paper reviews and discusses various literature relevant to the topic of transmission system development in a low-carbon energy system. It contains an overview of power system operability, an explanation of some key terms, and some examples from Great Britain ("GB"). Power systems are complex; yet they must be designed and operated safely, securely and economically. It is necessary to introduce a number of high-level concepts which are important to provide context, whilst resisting deep technical detail.

An introduction to power systems

Power systems connect supply (sources of power, largely generators) to assets which demand power (industrial, commercial or domestic customers). Power is measured in megawatts ("MW"), and Energy (the product which is generated) in megawatt-hours ("MWh"). Governments should ensure that there is sufficient generating capacity[1] available and operable to meet maximum expected demand. This is called **adequacy**.

Power is generated with a three-phase alternating current, and generators operate synchronously[2] with power systems. Key power quality characteristics (including frequency, voltage and power shape; see figure 1, Ref. (1)) must be controlled in order to maintain the synchronicity of all assets. Individual **transmission-connected** generators must maintain their own synchronicity with the system.

Great Britain's National Grid Company ("NGET") define this topic area as **system operability**, specifically: "the ability to maintain system stability and all of the asset ratings and operational parameters within pre-defined

[1] i.e. The maximum achievable level of power generation which may be connected to the Electricity Transmission System ("ETS")

[2] i.e. in phase

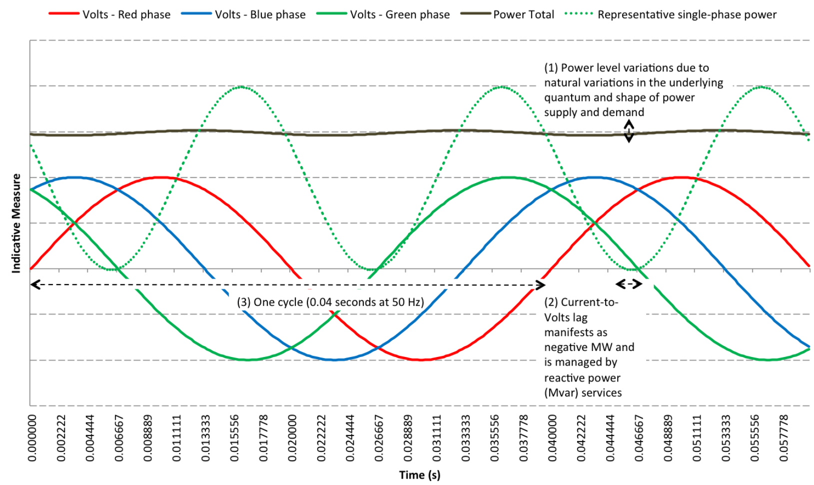

Figure 1: The key characteristics of power quality which require control to preserve system stability

limits safely, economically and sustainably" [1]. Protecting the synchronicity of a system when an asset operates outside of normal expected parameters is also important, and an ETS with **strength** and **resilience** will perform better in this regard than will others. Importantly, system operability is concerned with maintaining a system within normal parameters as well as protecting a system when **fault conditions**[3] occur; and returning it to an expected condition.

In essence, power demand, or **load**, and power supply must be balanced. Frequency must be maintained at all times. This requires the right generating assets to be connected and disconnected at/from the right power levels, and at the right time. This can sometimes be at short notice, in response to emergent (fault) conditions.

In a liberalised energy market[4] generators **schedule** themselves to generate in response to whether a market price signal is above or below their **marginal cost of generation**[5]. Typically, nuclear power plants ("NPPs") and renewable assets have low marginal costs and therefore generate as much

[3] i.e. Operation outside of normal parameters

[4] As is common in Europe

[5] The cost of generating an additional MWh, usually including variable fuel and transmission costs

as they are able to, when they are available. Thermal and hydro plants have higher marginal costs, therefore require higher market price signals to generate. All generators produce active power (MWs) and to balance a system, the active power generated must meet the system load at all times.

In many systems, it is for the generator to decide whether, or how, to respond to a near-real-time instruction to raise or lower power output. Balancing the system is generally a **commercial service**, which is particularly suitable (i.e. operationally practical and economic) for fast-response thermal plants. System Operators may however wish to strike expensive contracts with other generators in order to protect against highly unlikely, but severe, faults.

When generated power is higher than system load, generators must be scheduled off. Generally this happens commercially through market signals. In extreme cases, baseload generators[6] may be **curtailed**, meaning they are required to provide downward flexibility to achieve system balance, possibly "below [their] minimum output level and [in extremis] disconnecting from the system." Downward flexibility which is ready to be called upon is called **foot room**. "At the same time, there must be sufficient generation part loaded, ready to pick up for a generation loss; known as **headroom**" [2].

The voltage level on the system is dependent on the type and quantity of generator and demand load connected to the system at the time. Over-volts occur when power demand is low and load is too light. Voltage collapse occurs when load (particularly from heavy inductive machinery) is too high. **Reactive power** (Measured in Mvars, see figure 1, Ref. (2)) helps to maintain voltage levels, and their provision by generators is a **mandatory service** in many power systems.

System frequency must also be maintained[7] (see figure 1, Ref. (3)). Unless generation is scheduled to match demand, when system load increases, system frequency dips; and when system load is lightened, frequency increases. Because demand fluctuates continuously through the day, frequency must be continuously managed, and generators must therefore provide **frequency response** ("FR") services. Under FR, generator output is raised on receipt of a signal from the system operator of a falling frequency; and reduced on receipt of a signal from the system operator of a rising frequency.

[6] i.e. Those that are generally generating whenever they are available

[7] Generally at either 50 or 60 Hz. The GB's National ETS (the "NETS") operates at 50 Hz

Service	Response to	Initial response	Enduring response
High FR	Over-frequency	Decrease MW over 0 - 10 seconds from instruction	Sustained at no lesser reduction
Limited High FR		Decrease MW to available plant capability in extreme cases	Sustained where possible
Primary	Under-frequency	Increase MW over 0 - 10 seconds from instruction	Sustained for at least a further 20 seconds
Secondary		Increase MW available within 30 seconds of instruction	Sustained for at least a further 30 minutes

Table 1: GB Grid Code definitions of frequency response services [3]

FR is generally a mandatory service, but due to the impact of FR on MW output[8], generators will usually determine the price they would accept for FR services. See as an example the definitions used in GB, listed in table 1.

If a sudden and unexpected disconnection of either demand or generation occurs, frequency may change rapidly. **System inertia**, a measure of the kinetic energy stored in rotating machines which are directly connected to the ETS, helps protect the it against rapid frequency changes. A system with high inertia is less likely to experience rapid system changes and will therefore be more **stable**, reducing the risk of faults escalating into wide-ranging effects on generators and customers [1]. An important metric is the **rate of change of frequency**, ("RoCoF"). System inertia is a phenomenon uniquely important to ETS with low levels of interconnection to other, larger, systems and is discussed in a GB context more fully in "Characterising the growth of RES in Great Britain." **Ancillary services** are all those services which support ETS stability and operability.

Generating assets are not only connected to transmission systems. Many smaller generators are linked either to customer connections or distribution networks; these are called **distribution-connected** generators. Their effect

[8] Output remains the main source of generator income

Authored by: Si.Gillett@humbeat.co.uk

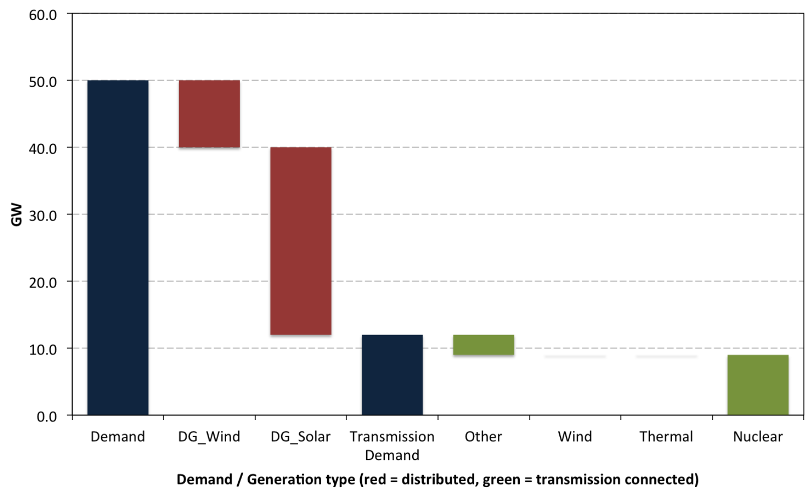

Figure 2: Representative distribution and transmission network connections contributing to transmission system demand

is to contribute to meeting national demand, but because of the way they are connected, they effectively self-dispatch when they are available and offset national demand, thereby reducing the transmission demand level which **transmission-connected** assets must meet. A graphical explanation may be found in figure 2. Some of the most relevant differences between transmission and distribution generator characteristics are listed in table 2.

The growth of renewable energy sources and their impact on electricity transmission systems

Energy system transformation away form large, grid-connected, dispatchable thermal power plants is underway. An increasing capacity of renewable energy generating assets are being connected to electricity transmission and distribution systems in many countries around the world each year. Coupled with a trend to deregulate energy markets, decarbonisation is being fuelled by government policy and incentives, but implemented by many independent commercially incentivised organisations.

Muench *et al* [4] list the characteristics of “volatility” and “many-players” to be two significant contributors to energy system complexity, therefore con-

	Transmission	Distribution
Description	Connected to ETS at high voltage.	Connected to distribution network at lower voltage (distributed) or into end-use customer systems (micro). Collectively called distributed generation
History	Generally 25+ years old, nuclear, hydro, coal, oil or gas plants. More recently large wind and biomass plants	Generally newer except for some smaller run-of-river or CHP assets. Wind, solar and small-scale diesel or biomass generation dominate the fleet
Size	Typically large (>500 MW)	Typically small (<50 MW) to very small (single KW)
Technical compliance	Required to conform to regulations and standards for critical service provision and response characteristics	Minimum technical thresholds are more relaxed but increasing as a result of system interconnection requirements
Dispatch	Centrally dispatched with known reliability by the Transmission System Operator	Locally dispatched with unknown reliability outside of the control of the TSO
Measurement	Metered to a high degree of accuracy	Largely unmetered
Contribution to balancing	Offsets national ETS demand; varying flexibility	Reduces national ETS demand; potentially flexible if central control difficulties are overcome
Contribution to inertia	Large due to heavy rotating generators and turbines	Small due to prolific use of power electronics

Table 2: Characteristics of transmission- and distribution-connected generators

sider them to hamper energy system transformations. The highly politicised nature of this sector is such that the long-term regulatory stability required to build confidence for investors in large, long-life power plants cannot be relied upon:

> "Important regulations in the energy industry ... have not been consistent in the past. This contrasts with the rather long term planning in this industry, where capital equipment usually last 20 years or even longer." [4]

As a consequence, as conventional plant closes, only a few new conventional plants open. Renewable energy systems ("RES") take up the gap, thereby significantly increasing their market share. The implications of this change are only now becoming clear.

This phenomenon is currently being experienced in GB: figure 3 uses data available from the NGET's *TEC register*[9] to illustrate that within 15 months starting September 2015, installed generation capacity in GB is expected to fall by 4% (or 2.7 GW) and thermal plant capacity will fall by 5.3 GW (or 12% of its total).

Muench *et al* go on to conclude that the "stability of energy transportation systems is at risk" [4]. Further, that politicised incentives for industry-led low-carbon investments may go some way to meeting the aim of decarbonisation, yet may also introduce a risk to system co-ordination and function. This is because the integration and operation of different generation assets has not been fully considered.

[9]Transmission Entry Capacity, a measure of the maximum net export of power from each generation asset to the transmission system. The TEC register records the operating dates, capacities and asset types of all existing and approved generating assets connected to the NETS

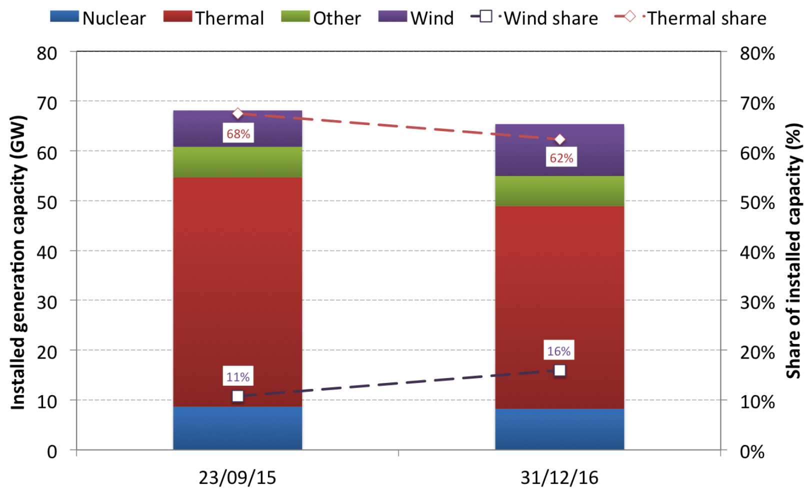

Figure 3: Increase in the share of installed capacity of RES and traditional generation assets in Great Britain between 23 September 2015 and 31 December 2016. Source: National Grid TEC Register

This is not a new opinion. Grubb discusses the integration of RES and their likely effect on ETS in his 1991 paper [5]. He foresees that capacities of RES[10] will not be limited; and therefore that "proper management" of those capacities (alongside any remaining conventional capacities) will be required in order to maintain a stable ETS. Specifically the need for increased operational flexibility of existing thermal assets[11] is foreseen observing that "Most large baseload units, nuclear and thermal, can be run stably down to at least 50% capacity" [5].

In foreseeing a need for existing assets to contribute to system stability in a different way in the future to that in which they had hitherto operated, Grubb identified three important considerations for ETS operation: rate of change of frequency; control and containment; and reserve operation. Grubb expands on how an increase in RES influences each of these considerations, and insight is provided as to how they may be managed in the future. The critical issue is how important each ancillary service becomes in a future energy system, and how capable the generation assets connected to that

[10] Especially wind and solar generation

[11] Many thermal assets before 1991 ran at either full load (baseload operation) or were left idle, leaving alternate expensive peaking thermal plant (e.g. oil fired power stations) to deliver flexible operation

Challenge	Description	Implication
Uncertainty	Weather forecasts incur an inherent unpredictability bringing uncertainty to both demand and supply sides of the power balance equation.	Power cannot be stored; therefore more near-term actions will be required to balance the power system as renewable generation capacities increase.
Local Specificity	RES assets must be built to complement the local environment, in order to maximise yield.	A localised preference for most suitable technologies will emerge, introducing local issues to national transmission systems; an additional management complexity
Variability	While weather forecasts incur uncertainty, the weather itself is also variable.	Over timescales of hours, days, weeks or seasons, generation from renewable assets may be very different yet demand and supply must be balanced, with implications for reserve and conventional plant

Table 3: Challenges of intermittent asset variability in power systems [6]

system are to provide that service. In other words, policy makers should seek advice on whether future energy systems are capable of stabilising themselves through the provision of sufficiently available and reliable ancillary services, either through mandation, or contracting.

Ueckerdt *et al* [6] describe from an analytical basis the challenges of wind and solar variability in power systems; these have been categorised into three groups and are described in table 3.

Uncertainty may manifest in that the level of the demand or supply of power may be much higher, or much lower, than was expected at any point in time. Yet it is a fundamental property of all electricity systems that demand and supply must be balanced at delivery. Improvements in demand and supply forecasting would help minimise balancing effort, however both upward and downward regulation must also be considered in order to protect the system against emergent imbalances.

An example of *local specificity* is that North-western Europe has potential for plentiful wind generation but has low solar generation potential. Northern Africa is the opposite. Darwin showed that for biological systems, variation and diversity provides strength. The same is true for energy systems, in that a system consisting of diverse intrinsic asset risk profiles is less susceptible to extreme conditions than a system with homogeneous intrinsic asset risk profiles. Thus the local specificity of power generation technologies introduces a degree of weakness into local power systems, implying the need for greater interconnection of the local power system with other areas, or greater local ancillary service provision to maintain wider system strength.

Variabiltiy is best described by the difference between summer and winter power demand. Some variability may therefore be broadly forecastable. However the traverse of a weather system, through an area with significant RES installed, may introduce very localised and time-bound variations in generation from solar PV or wind assets. In order to match demand with supply in all but the most inconceivable situations, it is important to be able to turn up or down enough of the dispatchable (i.e. controllable) plant remaining connected to the ETS. Flexible plant are important; inflexible plant may become a burden.

Policy makers are most concerned with adequacy, yet increasingly [7], foot room is becoming a concern for system operators. Foot room is not an operability issue in systems with very low capacities of inflexible plant, as flexible plant may reduce its output to meet demand lows. This can be called load following. More generally, **flexible operation** can be defined as any change in planned generation levels driven by non-plant related issues, e.g. commercial or ETS-related drivers. Any systems with significant capacities of inflexible generation[12] must consider how to manage any future foot room complexities.

Ueckerdt *et al* conclude that "all integration challenges increase with penetration" [6]. Identifying and mitigating system ancillary services shortfalls, and understanding and resolving foot room and adequacy concerns, are two important considerations for future system operability, made more complex by a lack of planning [4].

[12] i.e. Generation assets which will not change their power output for any but the most onerous external operational events

Nock *et al* [8] illustrated in their paper that:

> "The potential of wind participation in energy and ancillary markets enabled by wind control [is] ... an effective solution strategy among the other available solutions" [8].

However it is also noted that:

> "High variability in wind generation together with demand side variations causes increased requirements for ancillary services and cycling in conventional generation plants" [8].

It has already been demonstrated that others (e.g. Grubb [5]) agree with this conclusion.

Characterising the growth of RES in Great Britain

Under European legislation, NGET are required to issue an annual report designed to improve visibility to market participants of developments in the NETS. Through a process of industry and expert consultation, they have developed a series of three reports for GB, which are:

1. Future Energy Scenarios ("FES"), which establishes scenarios describing future NETS characteristics;
2. System Operability Framework ("SOF")[13], which describes the implications of those scenarios on system operation, and describes important mitigating actions; and
3. Electricity Ten Year Statement ("ETYS"), which describes specific investment and strengthening work required over the next decade to meet the needs of the changing system[14].

[13]It is foreseen in FES that a system which undergoes significant swings in demand and/or supply on a daily basis will be challenging to keep stable; hence the need for a second NGET publication, the SOF, which describes the ancillary and operability services required to balance a high-RES system

[14]ETYS is concerned mainly with local transmission system investment issues, and its contents are not discussed further in this dissertation. It remains however an important document for understanding how the NETS will develop to meet future challenges and risks

Together these documents help NGET identify and prioritise development work required to keep power flowing to customers safely, reliably and economically. They demonstrate that the NETS is undergoing a significant policy-driven transformation, away from large capacities of dispatchable thermal plant with a nuclear baseload capacity, and towards increasing capacities of both transmission- and distribution- connected renewable generation. This ongoing paradigm shift is expected to impact a number of critical parameters for the operation of the NETS.

The 2015 FES [2] described a future of increasing variability and interconnectedness. This theme has been continued into the 2016 edition. Four future scenarios have been developed by analysing prevailing policies and extrapolating their impacts. Each is constructed to describe reasonably foreseeable views of the future under different implementations of existing policy. Four key themes are communicated through the FES, namely: readying existing generation assets to respond to significant changes; managing the introduction of new assets; managing system headroom and foot room; and the resultant impact on the variability and uncertainty of demand / supply balancing requirements. These points are now described in turn.

Impacts on existing generation

Existing “thermal” generation, in line with conclusions drawn in “The growth of renewable energy sources and their impact on electricity transmission systems,” is expected to be the backbone of flexibility provision in all future energy scenarios, recognising that “balancing challenges are likely to increase” in each [2]. Closures in fossil fuel stations (a result of new environmental legislation and reduced operating profits[15]) mean that the pool of assets from which to contract ancillary services will be smaller in the future than it is in the present, as illustrated in figure 4. Existing assets[16] may be required to “work harder” to provide sufficient ancillary services to ensure system stability, with RES expected to be capable of meeting only a portion of the system’s ancillary services needs themselves.

[15] Reduced operating profits arise from shorter running patterns because of the effect of renewable technologies on power price

[16] Critically, potentially including NPPs

Managing the introduction of new assets

GB energy policy has prioritised two aims: **sustainability** (through the share of generation which is low-carbon) and **security of supply** (through the adequacy of generation to meet demand). Minimising costs also remains important. Investments in order to ensure system adequacy are being incentivised through the introduction of a loss of load expectation ("LOLE") metric[17]. This metric models the probability of system inadequacy (due to insufficient supply) at periods of high demand. To meet the LOLE standard it is recognised that an increase in generation capacity will be required. Much new capacity is expected to be from RES (especially solar and wind) and government is incentivising developers to deliver their policy ambitions. **Capacity credit** models generation outturn as a ratio of an asset's installed capacity. Due to the inherent intermittency of natural sources, RES assets attract a lower capacity credit than dispatchable thermal plant; hence more RES capacity must be commissioned to meet LOLE requirements than would be required of conventional plant. That the consequences of pursuing policy ambitions of sustainability and security of supply will result in a significant increase in the complexity of system operation has been demonstrated in "The growth of renewable energy sources and their impact on electricity transmission systems".

Critically, by adding significant capacities of intermittent RES to the ETS to assure generation adequacy at times of peak system demand, the risk of creating an over-supply of capacity at times of low demand is increased. This will be particularly true at times of bright sunshine, strong winds, or both.

Headroom and foot room

The FES describes in all four of its scenarios such situations where ensuring adequacy during high demand scenarios challenges the maintenance of adequate foot room during periods of low demand. Significant capacities of solar and wind generation are expected to be built in GB over the next 10 to 20 years, as demonstrated in figure 4. NGET expects that this trend will make the challenge of ensuring the NETS remains stable at all times (especially through periods of low demand) even more complicated than it is

[17] This metric influences frameworks for investment in new plant as well as penalties for existing plant which fail; a carrot-and-stick approach to ensuring reliability and investment to meet future energy needs. LOLE is agnostic to generation type

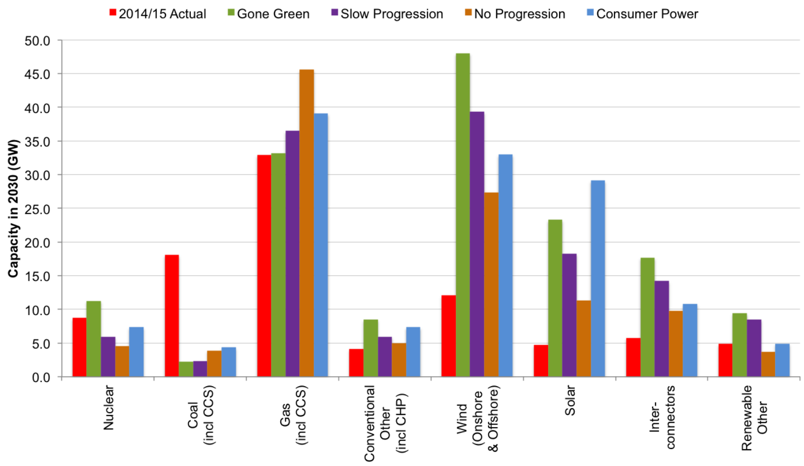

Figure 4: 2030 Installed generation capacity by asset type and NGET scenario [2, From Figs. 56, 58, 60, 62]

today. The FES echoes Grubb's view [5] of how foot room should be managed: through the flexibility of existing generation, including nuclear. This theme is continued into NGET's SOF document, where they are clear in their view of the importance of flexibility in any future nuclear plant [7].

Variability and uncertainty

Where mankind has developed the ability to harness power from the wind and the sun, we have not yet gained the ability either to control it, nor to predict it with a good level of certainty. The consequence is that expected swings in generation from renewable assets in GB could be as much as 16 GW over a 24 hour period in the mid 2030s [2]. Critically, the true magnitude of this swing may be known only very close to delivery. This implies that, under current GB energy policy, the size, urgency and frequency of essential system balancing actions should be expected to grow significantly in future years. The precise nature of the impact of this trend on the operation of existing generation assets (including NPPs) has not yet been fully characterised.

SOF identifies risks at the system level associated with system operability, yet the established definition of risk as used in British government documentation[18] is not consistently employed in the SOF. Situations are described, but their outcomes and likelihood of occurrence generally are not[19]. The consequence of changing important operability parameters is not yet fully understood; hence "closer collaboration" with the energy industry is cited as an important step in the future development of the SOF. Further work is required to translate SOF's emerging trends into risks which may be used as inputs to a probabilistic safety analysis or other consequence modelling.

It is clear that, as a result of pursing a policy of increasing RES, the NETS is undergoing changes similar to those being experienced in many other countries. It is also clear that the future is not well understood, and that research opportunities exist to interpret and resolve the scenarios as described in FES; and consider what their impact may be on GB's current and future nuclear fleet.

Grid operation and power quality

The challenges associated with integrating RES into ETS increase with their penetration [4]. Energy balance must be managed at all times; and as RES capacity increases, the difficulty in achieving balance when demand is either very high or very low also increases. Further, when demand is low and RES provide a significant share of total power generated, power quality and system stability also become difficult. Importantly, SOF describes the dynamic behaviour characteristics for a high-RES (i.e. low-inertia) network. Plant operation may be impacted upon by these characteristics, therefore they are listed and discussed below.

- Voltage and frequency may not evolve linearly in unbalanced or distributed systems and faults may evolve quickly;
- Generators may find it challenging to remain synchronous to systems following fast-evolving faults, increasing the risk of cascading faults;
- Fast-moving fault conditions will be more complicated and may not be predictable; and
- High-RES systems will be harder to mimic for test, research or safety justification purposes.

[18] Being a consequence associated with a probability of that occurrence

[19] This point may be addressed in the 2016 edition of the SOF.

The SOF [7] also describes two related concepts: *system inertia*, and *system short circuit level.*

System inertia and rate of change of frequency ("RoCoF")

The SOF foresees a significant decline in GB system inertia, resulting primarily in the requirement for increased frequency response services. Over the next 5 years, the requirement is forecast to increase by 30-40% [7]. GB's existing NPPs provide very limited frequency response capability. Thus with the expected closure or reduced running hours of many thermal plants, much system protection must be obtained in the form of synthetic inertia through frequency response services. Without sufficient procurement opportunities for system protection services, system protection settings and wider normal operating bands may instead be used to manage periods of low inertia.

> "Low demand periods ... present the most onerous cases for issues associated with the reduction of system inertia." [7]

Crucially, system inertia is a physical property of a power plant which, once synchronised, is independent of its generation output. The de-load of inflexible plant during low demand periods would create space for flexible plant to generate, thereby increasing both system inertia and frequency response capability, and reducing the likelihood of a system fault and the risk that brings to power plant electrical supply connections. The curtailment of inflexible plant not just for energy balancing reasons, but also in support of system stability is conceptually foreseeable.

RoCoF is closely related to system inertia in that RoCoF increases as inertia decreases. Plant electrical protection systems may not currently be sufficiently resilient, resulting in a generator trip if RoCoF is too high. In a low-frequency event, the subsequent reduction in generator load to the ETS may exacerbate the situation, increasing the chances of a cascade-trip or system blackout situation. This represents the most onerous form of Loss of Offsite Power event; and hence should be prevented if at all possible.

Short circuit levels and voltage dips

Short circuit level is a measure of transmission system strength, or its ability to remain within (or return to) normal operational states. Analogous to system inertia, the connection of large synchronous plants to the ETS maintains high short circuit levels[20], and levels are expected to fall as RES capacity increases. Critical system variables[21] may therefore enter emergency or unstable states more easily, more frequently, and potentially for longer periods in the future [7].

Short circuit level reductions increase the depth and geographical reach of voltage dips. Voltage dips have detrimental effects on generators and may cause disconnections or LOOP events if the dip is too deep or long-lasting. Voltage dips present a unique challenge for plant electrical protection systems as they are often unpredictable and unavoidable, and have a number of root-cause initiators [7].

In a system with a low short circuit level, generators at greater distances from a fault initiation location become more susceptible to those faults, implying an increase in the expectation that GB's transmission connected generating assets experience a fault in future years. By their presence, existing or new generating assets support short circuit level, therefore the relationship between future nuclear capacity, risk of LOOP events at inflexible plants and system strength is important yet complex.

In all cases, it will be important for electrical protection systems in power plants to be configured to be able to withstand higher RoCoF and lower short circuit levels, to allow the assets to continue to support ETS stability through ETS transients without jeopardising the safety of the plant or any of its own main or back-up electrical systems.

Conclusions

Three aspects of future transmission systems should be considered for grid-connected power plant operation. The first, *reserve capacity* is essentially an economic problem and, in the GB market, not directly connected to transmission safety and security considerations. As long as the system operator maintains security and power quality to within specific standards, no matter how those standards are met, there should be no impact on plant operation. *Power quality* is impacted by the characteristics of the generation and demand assets connected to the ETS at the time. Systems consisting of assets with wide-ranging load manoeuvring, frequency response and frequency maintenance capabilities will be more resilient against system faults

[20] "High" short circuit levels are more resilient than "low" short circuit levels

[21] Such as voltage or power flow

or unforeseen system balancing requirements. *Operability* requirements are likely to occur at periods of minimum ETS demand because at these times, transmission-connected generation outturn will also be at a minimum; therefore so will be the availability of supportive capability from those assets.

This document describes a change in the electricity sector. This change is driven by renewable generation growth; and is characterised as part of a global solution to a global problem, with different implications in different national ETS. The change has local characteristics, determined by the current state of the local ETS as well as local environmental aspects and policies which drive specific types of renewable generation growth. Change brings with it an increase in variability and uncertainty in transmission system operation; in particular in relation to the size and speed of demand / supply balancing actions. However in the future, highly technical aspects such as voltage control, frequency response and power quality are expected to require active management to permit the transmission system to operate as it is intended.

GB is no exception to this global trend, and its unique island geography make it particularly susceptible to certain anticipated operability effects. GB is undergoing a significant growth in embedded generation capacity, i.e. capacity which reduces transmission demand, rather than contributes to meeting it. Transmission connected generators should be mindful of these developments and how they may impact on their operational profiles.

References

[1] National Grid plc. *System operability framework.* National Grid plc, Warwick [online], 2014. http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/ [Accessed 13.12.2014].

[2] National Grid plc. *UK future energy scenarios 2015.* National Grid plc, Warwick [online], 2015. http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/.

[3] National Grid plc. *Grid Code, National Grid Electricity Transmission plc.* National Grid plc, Warwick [online], 2014. www2.nationalgrid.com/uk/industry-information/electricity-codes/grid-code/the-grid-code/.

[4] Muench, S., Thuss, S., Guenther, E. What hampers energy system transformations? the case of smart grids. *Energy Policy*, 73:80 – 92, 2014.

[5] Grubb, M. J. The integration of renewable electricity sources. *Energy Policy*, 19(7):670 – 688, 1991.

[6] Ueckerdt, F., Brecha, R., Luderer, G. Analyzing major challenges of wind and solar variability in power systems. *Renewable Energy*, 81:1 – 10, 2015.

[7] National Grid plc. *System operability framework*. National Grid plc, Warwick [online], 2015. http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=44046 [Accessed 15.12.2015].

[8] Nock, D., Krishnan, V., McCalley, J. D. Dispatching intermittent wind resources for ancillary services via wind control and its impact on power system economics. *Renewable Energy*, 71:396 – 400, 2014.