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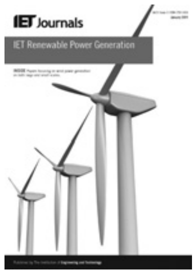

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System strength considerations in a converter dominated power system

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Abstract: The drive towards renewable energy sources (RES) is dramatically changing the dynamic electrical characteristics of Generators, which are traditionally the dominant dynamic component in Power Systems. Non-synchronous generation (NSG) approaching or even exceeding control area demand is now happening on a rapidly expanding scale. The study identifies from National Grid's perspective as Great Britain transmission system operator, the key challenges during periods of operation with high proportion of RES relative to demand. It raises some major questions. What determines system strength in an HVAC system largely without synchronous generators and what is adequate for stability? What levels of %NSG can be expected in the future energy scenarios? What are the financial consequences of constraining RES production if the technical capabilities create an upper limit of %NSG which the system can be operated at? The study finally proposes closer collaboration across the industry to find the optimal missing solutions.

1 Current status of stability aspects

Prabha Kundur *et al.* (CIGRE and IEEE) [1] established an overall high level view of the different classes of stability in a power system as illustrated in Fig. 1.

Stability analysis has traditionally been based on physics of electrical machines founded in general machine theory. However with the introduction of renewable energy sources (RES) stability is becoming increasingly dependent upon complex control systems associated with converters.

In the new world, under high RES operating conditions with modest demand, stability is determined not just by physics of electrical machines, but by the choices made by a range of system designers, most notably by transmission system operator (TSOs) setting Grid Code performance requirements and by converter designers.

The paper focuses on HVAC system stability and starts from the premise that total system stability is still adequately described by the main categories of angular, voltage and frequency stability. The main focus is on angular stability (maintaining synchronism) for large disturbances in a power system with synchronous generators (SGs) making up less than 50% of generation under some real time conditions, with the possibility that it may be close to 0% in the future.

In many future power systems the power input will predominantly be sourced from converter interfaced RES when windy and/or sunny conditions prevail. Traditionally converter designs have focused on the needs of the converters themselves (e.g. survival during faults) rather than the needs of the HVAC power system. Dominance of RES and HVDC is developing rapidly. In Western Denmark wind production has exceeded total demand at times of high wind. However, in this case the impact on this Control Area is mitigated by 400 kV connection to the rest of Continental Europe which provides the necessary mass of synchronous machines. Existing development plans in Ireland and then Great Britain (GB) expands the prospect of converter dominance to complete synchronous areas (SA) as these areas have no synchronous links to the continent. New Offshore AC islands connected to the onshore power system by HVDC systems (e.g. large and remote wind farms in the North Sea off Germany and GB) also face this challenge. Four such AC islands are expected to be commissioned in the German sector of the North Sea by the end of 2014.

For the smaller SAs such as GB and Ireland, frequency stability was identified as a major challenge early on. The GB Grid Code in 2005 introduced requirements for frequency response capability of RES, mainly wind power plants which were equivalent to the capability demanded of SGs [2]. However subsequent to this, two further frequency management challenges have emerged relating to frequency range and rate of change of frequency (RoCoF). These aspects affect a large number of deeply embedded but mainly small generators. Work is in progress to bring frequency related behaviour of these generators under control, ready for further connection of RES capacity. In GB the total system inertia is predicted to reduce by a

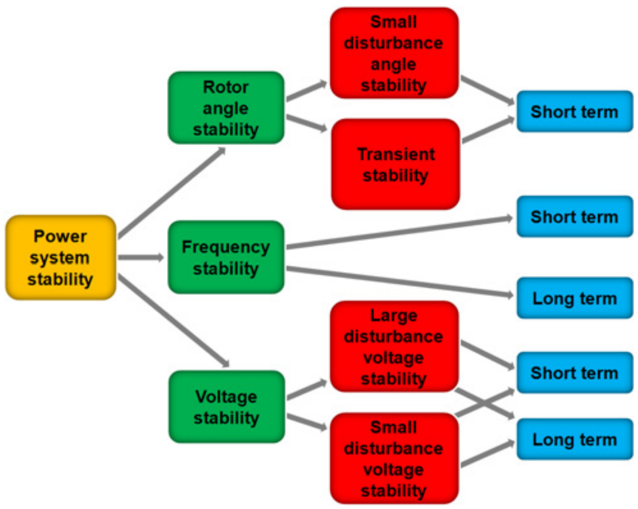

Fig. 1 *IEEE/CIGRE stability classification diagram [1]*

factor of about 5 from 2010 to 2030 [3]. Measures to improve the total system inertia are being considered from a wide range of sources [4–8].

TSOs also face new challenges associated with voltage management as the SGs, previously the main source of steady state and dynamic reactive power reserves, are increasingly replaced by converter dominated RES power sources. Again in GB the Grid Code, as issued in 2005, established similar requirements for reactive power and voltage control ensuring non-synchronous generation (NSGs) provide similar services [2]. Reactive power exchange (steady state and dynamic) between transmission and distribution is also becoming increasingly important for voltage stability. The proposed European Network Code 'demand connection code' [8] covers three measures to bring reactive power exchange (transmission to distribution) under control. This includes low demand conditions when controlling high system voltage is particularly challenging, in a much more severe way than previously experienced by TSOs.

Larger power transfers over longer distances are increasingly happening and expected to further accelerate as Europe moves towards a single market in electricity, planned to be ready by end of 2014 [9].

In HVAC systems the above transfers are sometimes limited by small signal angular instability (power oscillations). One such area of concern in this respect is the AC interconnection between Scotland and England. A National Grid paper [10] covers 'Considerations of future Small Signal Stability in GB Networks'.

These same interconnectors were chosen as the fault location for the case studies described in Section 4. The focus of Section 4 is on transient angular stability rather than on damping of power oscillations (small disturbance angular stability). In an increasingly converter dominated power system, the concern associated with power oscillations diminishes, at least if fast acting voltage control measures for wind power parks as required by GB grid code [2] have been properly implemented as in GB [2]. These GB WPP reactive controls may not be common in other countries where use of much slower power factor control has been common.

2 Analysis of 2030 hourly production focused on the level of NSG

2.1 *Definition of %NSG*

This should be determined in respect of real time operation of a synchronous area (SA) rather than annual averages. The real time RES penetration (%NSG) has been observed to be up to 5 times higher than the annual average penetration (e.g. when Denmark exceeded 20% on annual average from wind, 100% was observed in real time for some hours in the year). Initially a simple % of NSG production (P_{NSG}) relative to demand (P_{Demand}) for the separate AC system in GB was used. The authors have found that this simple principle can be extended to cover import and export. Import to the GB SA via HVDC links adds to NSG production. Export is effectively a further demand. Consequently a more comprehensive definition of %NSG for the GB SA is described below, which includes exchanges by HVDC with other SAs ($P_{\text{HVDC\_import}}$ and $P_{\text{HVDC\_export}}$) as follows

$$\%\text{NSG} = 100\% \cdot \frac{P_{\text{NSG}} + P_{\text{HVDC\_import}}}{P_{\text{Demand}} + P_{\text{HVDC\_export}}} \quad (1)$$

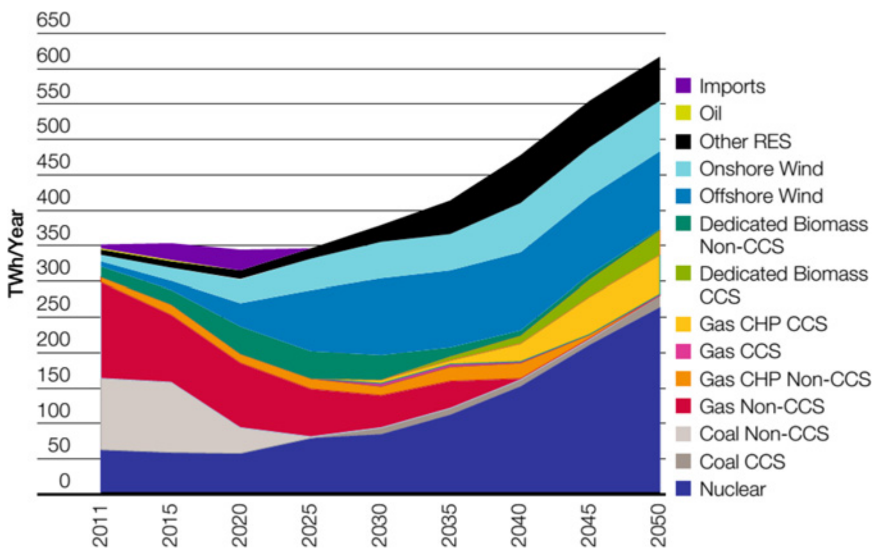

Fig. 2 *GB future low carbon electricity generation background [11]*

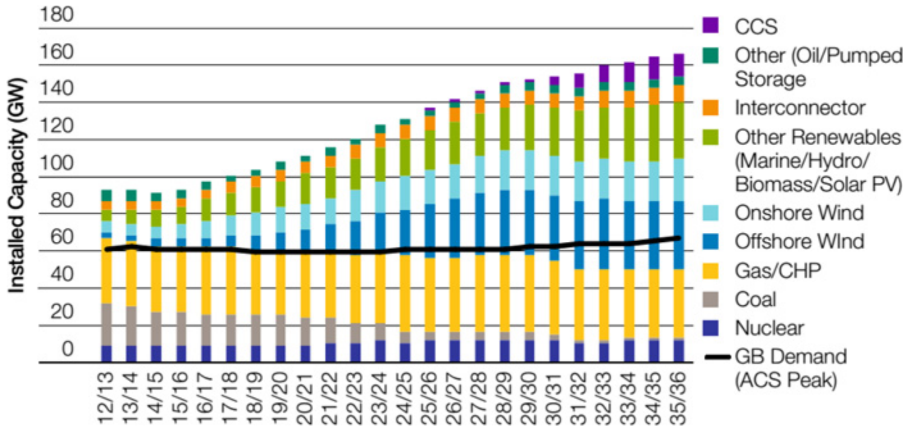

Fig. 3 *GB future demand and generation background under the 'GG' scenario [11]*

2.2 UK energy scenarios

In July 2013 National Grid published its annual document on UK future energy scenarios (FES) [11]. FES covers two scenarios, gone green (GG) and slow progression. This paper focuses on the more challenging GG, which results in a higher volume of converters. Fig. 2 covers energy production out to 2050 in its GG scenario, which meets the environmental targets. On and offshore wind as well as 'Other RES' can all be considered NSG. Fig. 3 shows that from 2030 there is enough capacity of each of NSG and SG to meet the GB demand on their own, that is, GB without imports is expected to have enough cover for max demand when there is no wind or sun available (e.g. a winter evening with a dominant high pressure weather system).

Fig. 4 shows the result of modelling of the 2030 GG scenario, which has a combined installed capacity of wind and photo voltaic (PV) of 73 GW. The predicted wind and solar output and associated total GB demand for the year 2030/31 has been modelled. The modelling is achieved through scaling according to 2030, the zonal production capability by individual projects as defined in the FES data [11]. It is based on recorded 2012/13 wind in each zone (giving widespread representative locations both on and offshore). Regarding PV production, this is based on hourly solar intensity recorded at a single location – Birmingham, again scaled to the FES installed capacity for 2030. In Fig. 5 the same RES production is expressed as % of total GB demand for the same year. It shows the % of NSG varies greatly, with the highest unconstrained value reaching 160% of the total GB demand in the Christmas period. This part of the analysis assumes zero import to GB and zero export from GB throughout.

2.3 Energy substitution implications of varied system capabilities to operate at high %NSG

Many operability challenges arise from a range of technical issues linked to high %NSG. Some of these issues are briefly listed in Section 1, whilst others are covered later in this paper. Many of the boundaries of operability for individual technical issues can be expressed as a %NSG beyond which the system cannot be operated, at least not until mitigating actions have been implemented. At any time, (e.g. in 2030 with GG as focused on here) the overall operability is the lowest of these %NSG boundaries. Analysis has been undertaken of the consequences of a variety of overall %NSG operability limits between 50 and 95%. The summary of this work is presented in Table 1.

Table 1 illustrates the necessary level of energy substitution from NSG to SG (expressed in TWhs) calculated for various overall system stability capabilities from 50 to 95% NSG. It is based on the data arising from the energy production

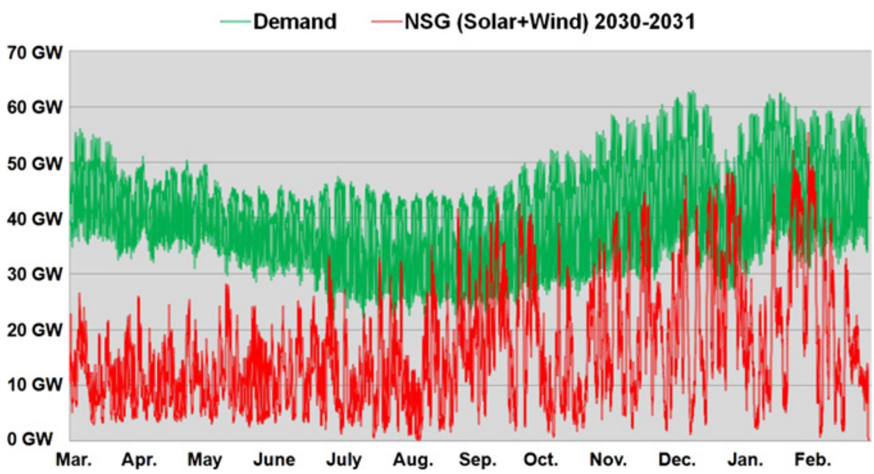

Fig. 4 *Hourly NSG (Wind and PV) active power output (in red) compared with demand (in green) in 2030/31 (March–February) scaled from 2012/13 recorded data*

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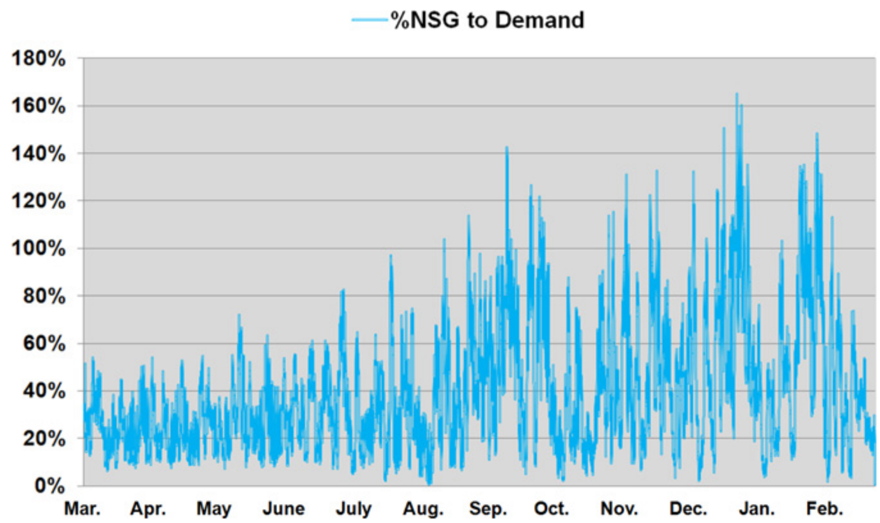

Fig. 5 *GB hourly NSG as % of GB demand for year 2030/31 with GG production*

modelling defined in Section 2.2. This analysis has initially been undertaken without any HVDC import/export. Then three other cases were studied with different combinations of 0 or 10 GW export (to Continental Europe and Nordic SAs) and 0 or 3 GW import (from the Irish SA) to establish any sensitivities. These import/export levels are higher than the GG2030 connectivity.

Figures in *italic* indicates close to unconstrained operation (<1 TWh substitution of NSG with SG), and figures in **bold** high level of substitution (>5 TWh). These TWh figures should be seen in relative context of a total GB annual demand of 350–400 TWh. Hence, the **bold** figures indicate constraints in excess of about 1.5% of the total energy or about twice that (3%) of the total annual RES production.

Substantial system technical capability improvements would have to be made on many topics well before 2030 in order to bring the system operability up to the level of the *italic* part of Table 1, allowing %NSG as high as 95% with 3 GW import from Ireland or even with the lesser 85% required if no import from Ireland is factored in. This starts with resolving inadequate system inertia followed by tackling lack of reactive power in central parts of the system. A number of quality of supply (QoS) aspects and some new protection challenges will also need attention. Inadequate synchronising torque is discussed later in this paper. It would additionally require the construction of a lot of interconnectors (up to 10 GW) with Continental Europe and the Nordic SA.

2.4 Technical limits with high %NSG on system strength

Associated with the stability factors described in Section 1, there comes a point when each of these factors separately becomes a limit for stable operation. To go beyond all of these limits it is necessary to implement mitigating actions. The overall system stability capability can in principle be described as a %NSG system capability, at least for those aspects with a system-wide character rather than local character. When considering existing position and various scenarios with planned mitigating actions taken into account, then a %NSG capability could be ascribed for each year or each 5 year period ahead. Ideally the mitigating actions should be kept ahead of the increasing need to operate at progressively higher %NSG. For economic and environmental reasons it will be necessary to avoid constraints of more than a modest percentage, say 1%. This will avoid or at least reduce the required limitation on RES production.

Limitation on frequency stability relates to a complete SA. One illustration of such a limit already being in operation is for Ireland where a limit of 50% NSG is applied [12]. Above this limit further NSG production is substituted with SGs. The TSO in Ireland has an ambition to raise this limit to 75%. The system technical capabilities necessary to achieve all relevant forms of stability at these extreme levels of %NSG needs to be put in place at the right time. This may start 10–15 years ahead of those levels of %NSG in order to ensure compatible new plant (generators, demand and networks) is available in adequate volumes.

Modelling for load flow studies is still readily undertaken for the new situations described in this paper. The position is different for analysis of power system relating to fault levels (max and in particular min) and QoS. These areas introduce new major challenges for power system analysis (PSA) when studying high %NSG with the current analysis tools. It is critically important for system security to establish the dynamic performance under the lowest system strength operating conditions. This relates to staying within system voltage limits, angular stability, power system protection performance and commutation of line commutated converter (LCC) type HVDC. In addition the

Table 1 Annual level of constraint in TWh (NSG needed to be substituted with SG). Shown for increasing capability of overall system stability (expressed as %NSG) and for different levels of import/export

NSG%	3 GW Imp. 0 Exp.	No. Imp./Ex.	3 GW Imp. 10 GW Exp.	0 Imp. 10 GW exp.
50	**31.04**	**23.14**	**18.81**	**13.54**
60	**21.04**	**15.25**	**10.74**	**7.22**
75	**10.99**	**7.46**	3.81	2.29
80	**8.66**	**5.68**	2.59	1.49
85	**6.71**	4.31	1.72	*0.94*
90	**5.16**	3.27	1.11	*0.55*
95	**3.95**	2.45	*0.68*	*0.28*

consequences of extreme low system strength on QoS aspects of harmonics, voltage step changes and system unbalance needs to be well understood through analysis and brought into the design processes.

2.5 Optimising system technical limits

To constrain RES and substitute with SG is financially and possibly environmentally costly, replacing low CO2 intensity production (NSG) with potentially high CO2 (SG).

Here a figure for cost of substitution of £100/MWh (£0.10/KWh) is used for illustration. This analysis can broadly inform policy choices to move from low to higher NSG system limit. Substitutions of NSG contained below 1 TWh/year (£100 M) in 2030 under GB GG scenario is indicated by *italic* in Table 1. The analysis indicates that with no import/export a technical capability of delivering a stable system needs to be greater than 95% NSG as there is no *italic* in the second column in Table 1. Achieving stability with 95% NSG would be an extreme system technical challenge.

If export capability and available markets exists for 10 GW export (without further wind import from Ireland) then a lesser technical capability of stable operation around 80–85% NSG would be adequate (see boundary of bold in the last column). This level is still well in excess of any experience for a full SA. The highest known capability is 50% in Ireland. In GB the capability is currently very much lower, caused by frequency stability considerations arising from the potential mal-operation of RoCoF protections for deeply embedded generators.

3 System strength consideration and modelling

3.1 Measurement of system strength

Power system 'strength' [13] can be defined from two aspects: (1) its impedance which is made up of generators, transformers, transmission lines and loads; (2) its mechanical rotating inertia [12]. The higher the system impedance, the weaker the system strength and the greater the undesirable effects such as voltage variation. System inertia through machine rotating masses defines the system capability of maintaining stable frequency in the short term and also capability to stabilise the voltage angle variations. The latter is the focus for studies in Section 4.

With increasing numbers of AC/DC converters being implemented, the short circuit ratio (SCR) at a specific converter site is defined as the ratio of system short circuit level MVA (S) to the converter DC power MW (P_D) [12]. This is the preferred means of indicating system strength for such converter based systems

$$\mathrm{SCR} = \frac{S}{P_{\mathrm{D}}} \tag{2}$$

3.2 Impact of low system strength on synchronising torque

Synchronising torque can be defined by a single SG connected to an infinite bus system. At grid voltage angular change $\Delta\delta$ or speed change $\Delta\omega$, the SG will instantly change its electromagnetic torque ΔT_{EM}, which breaks into two components- namely synchronising torque with gain K_{S} and damping torque with gain K_{D}

$$\Delta T_{\mathrm{EM}} = K_{\mathrm{S}}\Delta\delta + K_{\mathrm{D}}\Delta\omega \tag{3}$$

From (3) it can be shown that the synchronising torque is normally associated with short-term angular change, whereas damping torque is associated with longer term slower often repeated angular changes. Damping of the latter is affected by damper windings added to generators, excitation ceiling voltage and excitation controls (e.g. PSS) in the relative short term and turbine governors in the longer term.

Even though Grid Codes (e.g. in GB) specify the frequency response and voltage control of VSC HVDC and RES converters related to the damping torque, the synchronising torque is not usually covered explicitly. The phase locked loops (PLL) in Converters (of VSC type), which rapidly tracks changes in grid phase angle and modifies the output voltage produced by its controlled converters, play an important role in maintaining synchronisation with the grid. Converters using PLLs do not vary the converters' power output for a grid rotor angle disturbance [14] unlike synchronous machines. Therefore the rate of change of phase angle with respect to the grid is typically allowed to change much more rapidly. This results in minimal synchronising torque (K_{S} close to 0) [15]. Synchronising torque has to date been barely provided by HVDC and RES converters [16].

3.3 Impact of low system strength on protection systems

Conventional power transmission systems are planned to carry the power from generation to the loads using EHV networks, with the design of the protection systems based on the predictable behaviour of SGs during faults. VSC-HVDC systems and various NSG converters are equipped with fast-responding controllers that impair system strength by preventing high currents and modifying the conventional electrical characteristics of power systems [4, 5]. This could result in new challenges for transmission protection systems, in particular

- Some older unit protections depend upon current impulse starters (quiescent/inactive during normal operation), leading to faults possibly not being detected because of absence of the required current impulse.
- Distance protection depends on the calculated fault impedance, which rely on almost instantaneous measurement of current and voltage. The fault impedance of VSC-HVDC and RES converters appears to be higher than the real value, leading to potential for protection mal-operations.

3.4 Impact of low system strength on angular stability

Low system inertia in a low-strength system will result in additional angular stability challenges. Particularly for the AC inter-connectors between two relatively weakly connected systems (e.g. England and Scotland). There is a potential risk of losing synchronism during critical fault events. This topic is the main focus of Section 4.

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3.5 Impact of low system strength on LCC-HVDC commutations

A power system with occasional low system strength, becomes a major issue regarding commutation of LCC HVDC links, as experienced in the Norwegian end in the mid 1970s for the 500 MW LCC between Norway and Denmark, prior to completion of system reinforcements. LCC converters require strong grid voltage source with high short circuit current to be functionally stable during faults. System reinforcements together with synchronous compensators placed at the LCC-HVDC connection terminal have provided the solution for many decades. A lesser contribution is possible from SVC/STATCOMs. However these may be inadequate in future NSG dominated operation with very low system strength. Whereas older HVDC LCC systems typically required a SCR >3, more recent LCC control system improvements allow SCRs down to about 2 [17].

3.6 Converter models

In the future, system strength is critical to operability and security and is consequently of interest to power system engineers. Currently, there are more questions than concrete solutions to be applied to adequately represent all variations in converter designs and control strategies. The authors suggest that analysis is performed to identify improvements that are required in the models and PSA tools to enable trust in stability studies when covering very high %NSG conditions, at least up to 90%.

Various groups in the IEC and CIGRE have been discussing and standardising HVDC and NSG models for a number of years, but the process is complex and slow and is not focused on operation with extremely low system strength. Studies performed by ENTSO-E and its member TSOs are very much dependent on these efforts and the possibility of exchanging adequate data between TSOs who are using different PSA tools. Consequently ENTSO-E members are investing significant amounts of resource in defining common information model (CIM) for data exchange and contributing to the IEC CIM standardisation work. ENTSO-E CIM standards are defining a library of standard models which have to be supported by all tools used for dynamics simulations by TSOs. The ultimate goal is to perform load flow and dynamics studies which are shared between TSOs as well as with ENTSO-E, that is, a high level of interoperability is expected.

Ensuring interoperability and adequate modelling will require substantial joint effort between TSOs and PSA tools vendors as well as research institutions. Postponing such activities may lead to inadequate system stability assessments.

In future, differences in control strategies need to be modelled in wider system studies to allow greater focus on optimal contribution to the performance of weak ac system. To date the focus has mainly been on the stability of the converters themselves and detailed models applied mainly for local investigations. One of these aspects is illustrated in Section 4.

4 Stability studies with a reduced GB model for the 2030 GG network

Studies were carried out on a reduced model of the England, Scotland and Wales Transmission Network, which was represented by 36 interconnected busbars/substations. Each substation in this reduced model represents a part of the system and connects all associated generation (including tens of GW of offshore wind), demand and HVDC Interconnectors (both internal zone to zone and international links) (Fig. 6).

The model reflects the Generation capacity of 2030 GG as per [11] and was dispatched using a spread sheet which connected and sized the MVA rating of various plant types accordingly. This model is available on request from National Grid, by contacting a National Grid author. Plant was dispatched by type and location taking account of real time available power from renewable sources. It was built using Power Factory V14.0.522.11. Dynamic studies were performed at a 2 ms step rate.

The 2013 full network version has been published in the 2013 GB Electricity Ten Year Statement [3]. The model used included dynamic controllers for Generators (including their Governors, AVRs and where appropriate PSSs) and for HVDC as well as SVC/Statcom converters. Various system reinforcements were made to accommodate the high levels of NSG in 2030. These include current and proposed works, for example, the series capacitors between England and Scotland and East and West Coast HVDC links.

With wind concentrated in Scotland and Offshore and new nuclear on the coast in southern half of GB, absence of voltage support in the central parts of the system was first remedied by blocks of 2 GVA STATCOMs. This is about 10 times larger than existing individual STATCOMs, but represents aggregated reactive sources at various substations. The absence of synchronous generation in Northern half of GB also presents a major challenge relating to stability.

A variety of dynamic simulation studies were performed to determine the maximum NSG which could be accommodated while maintaining first swing (transient) stability. The case

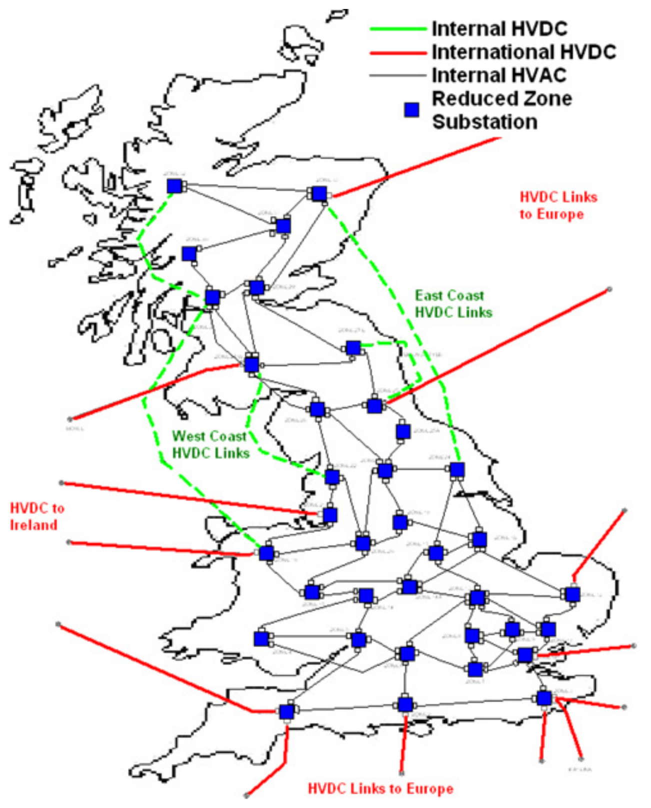

Fig. 6 *Reduced GB 2030 36 nodes transmission system model*

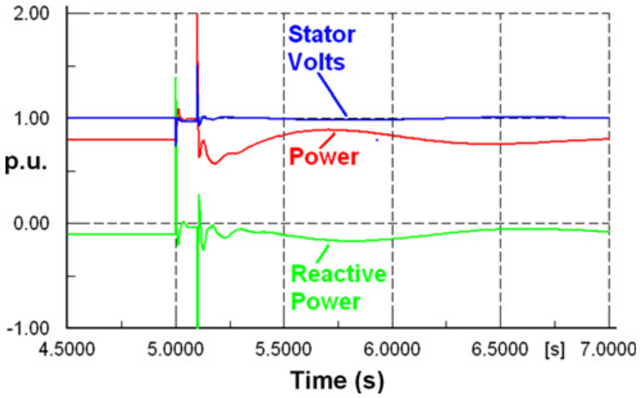

Fig. 7 *Power, reactive power and stator volts for a scottish synchronous generator – marginal stable case*

chosen was a double circuit 3 phase fault on 2 of the 4 HVAC links between Scotland and England. This fault which is commonly seen as the most severe credible fault in GB was initiated 5 s into the simulation and cleared 100 ms later at 5.1 s with the removal of the double circuit. It was found that exceeding NSG thresholds in the region of 65% of dispatched MW (typically 75% connected generation in terms of MVA), resulted in instability.

The instability was different to that traditionally found when dealing with SGs, being high frequency in nature, leading to a suspicion of numerical instability. Under these conditions the model quickly settles and the noise ceases. Fig. 7 shows such a case where noise occurs during or shortly after short circuit and switching events. The large equivalent synchronous generator (about 1000 MVA) plotted is located in South East Scotland.

However it was found that higher levels of NSG resulted in responses which become increasingly unstable, with large reactive, active power and voltage disturbance, ultimately resulting in synchronous generation pole slipping. Fig. 8 shows a case for a system that is unstable.

Various study cases were considered as summarised in Table 2, including combinations from varying three factors

• NSG production from RES High (37 GW or 50%), Medium (30 GW) and Low NSG (24 GW) from 73 GW of installed capacity.

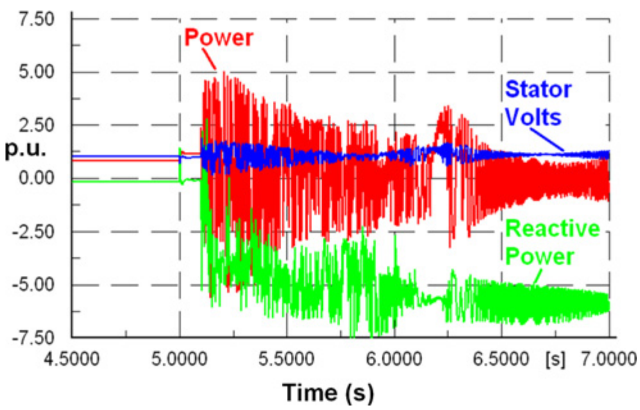

Fig. 8 *Power, reactive power and stator volts for a scottish synchronous generator – unstable case*

Table 2 Operating boundary in relation to NSG, demand, import and export

Renewable Generation	0 Import 0 Export			3 GW Import 10 GW Export			10 GW Export No. Import		
	Load, GW			Load, GW			Load, GW		
	40	35	30	40	35	30	40	35	30
low	√	×	×	√	√	×	√	√	√
medium	×	×	×	√	×	×	√	√	×
high	×	×	N/A	×	×	×	×	×	×

• Varied demand of 30 GW, 35 GW and 40 GW compared with present variation from 18–60 GW.
• Varied import and export from international HVDC links of 0 GW Import/Export, 3 GW Import 10 GW Export and 10 GW Export (these values exceed GG2030 interconnector capacities).

The NSG capacity in GG 2030 of 73 GW is made up of 57 GW wind, 15 GW PV and 0.8 GW Marine.

It is reasonable to expect maximum import from Ireland when high wind conditions occur in GB, as Ireland often experience high wind at the same time as GB.

The remaining generation merit order was determined by its type with priority given to nuclear then biomass, hydro and gas etc., respectively. A reference stability study was first undertaken without any NSG production (no output from wind and PV).

Table 2 highlights the stable operating boundary in terms of NSG for varied GB demand, import and export.

The absence of stability (X in the table which includes all cases with high RES) may either reflect on the suitability of the models used, a limitation of the current version PSA tool or the stability boundary of the real system. There has not been an opportunity in this limited work to determine the dominant factor.

Stability can be achieved by scheduling SG in place of NSG at the same geographic locations or installing and dispatching synchronous compensation. Nine GVA of synchronous compensation was required to maintain stability for even the most challenging case studied combining low demand, high RES production and no export. The large scale addition of synchronous compensators improves stability and other perfomance criteria such as fault level and system inertia. However, it is unlikely to be either the only or the most economic solution. In GB the modest installed capacity of synchronous compensators on the power system were decommissioned about 10–20 years ago, partially because of the high maintenance costs of rotating machinery compared with SVCs.

To enable converters (of VSC type) to improve synchronising torque, a VSC has to behave as a SG or at least possess some features of a SG (e.g. inertial response, frequency response and voltage regulation).

Therefore novel control strategies have been proposed for HVDC and NSG by adding or modifying the converter control with regarding to provision of synchronising torque [18], virtual power angle [14] and synthetic inertia [4, 5].

At the time of the final editing of this paper, National Grid has published its wide ranging System Operability Framework 2014 [15] providing further depth of context to many of the issues referred to in this paper.

5 Conclusions

Stable operation at very high NSG is becoming essential if the development towards RES based converter dominated power sources is going to continue. Analysis of wind and solar production in GB in 2030 under GG scenario has shown that without export capability and access to overseas markets, this needs to be in the region of 95% NSG. This would limit necessary RES substitution to 1 TWh per year. With 10 GW export (more than in GG2030) stable operation to a lower %NSG limit of 80–85% is adequate to still achieve the same modest level of substitution.

Initial studies focused on stability for double circuit faults on 2 of the 4 HVAC connections between England and Scotland. These indicated that stability is achievable for NSG up to about 65%. This leaves a significant shortfall requiring more than 12 TWh of substitution unless mitigation actions are implemented. Stability studies repeated after adding high volume of synchronous compensators (9 GVA) indicate that the required stability can be achieved and substitution is reduced back to 1 TWh.

Further collaborative work is needed across the industry, combining efforts from TSOs, PSA tool providers, university researchers and converter manufacturers to

- Establish the limit of PSA tools in terms of trustworthy stability analysis at high %NSG and modify, if necessary.
- Extend the initial narrow stability analysis in this paper for high %NSG conditions.
- Cover other aspects potentially affected such as protection performance adequacy, HVDC LCC commutation and QoS aspects, again in context of high %NSG.
- Define options for solution and analyse their relative merits. These are likely to include at least a mix of synchronous compensators and advanced converter controllers emulating Synchronous Generator performance.
- Review the adequacy of converter models as applied to large HVAC system studies in context of operation at high %NSG (e.g. impact of emulation and PLL functionality) and make them suitable for data exchange.

The above work should lead to definition of a way forward. These new system performance requirements would then be expected to be formally defined in Connection Network Codes in Europe and nationally in Grid Codes. To avoid excessive RES substitution, the new requirements may need to be in the codes 10–15 years before the system need for them arises in order to be effective.

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