Report to PIU

Network security of the future UK electricity system

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1. Scope and summary of the report

1.1 This report discusses the security of electricity supply in the present system dominated by large gas, coal and nuclear generating plant and future systems characterised by a large penetration of embedded generation technologies including renewables, CHP, micro generation and demand side management.

1.2 This discussion is placed in the context of the UK with particular reference to the 2010 Government targets for renewable energy and CHP. Furthermore, system security in the medium-to-long term (2025 and beyond) with a considerably larger contribution to electricity supplied from embedded generation is discussed (see Appendix for a brief description of system security and the term “Network Security”).

1.3 For the 2010 targets the main priority will be to *integrate* the operation of embedded generation and *distribution networks* and no significant issues related to system security are likely to emerge. A large proportion of the costs of accommodating this generation into the UK electricity system will be associated with connections to distribution networks, rather than with maintaining system security.

1.4 In the medium-to-long term, with a considerably larger contribution of electrical energy supplied from various forms of embedded generation, and in particular with the connection of large-scale intermittent renewable sources, maintenance of system security will require *integration* of this generation in the operation and development of the *entire* system. Balancing demand and generation will be a matter of primary importance for maintenance of system security of future sustainable electricity systems. The methods of achieving secure operation of such a system and the associated costs have yet to be determined. Further investigation of these areas is urgently required.

2. Issues for 2010

Distribution system operation

2.1 Under the present conditions the owners and operators of the distribution networks, the Distribution Network Operators (DNOs) anticipate that they can integrate only a very limited capacity of generation [1] without major reinforcement. Hence, the potential bottleneck for the 2010 targets is the distribution system, and it may be necessary to change the operational practices of distribution networks in order to accommodate the expected increase in renewable and CHP generation.

2.2 The environment in which distribution companies function leads to a number of interrelated regulatory, commercial and technical questions that need addressing in order to facilitate this growth in generation. This reflects

(i) the historic function of the distribution network, that has been primarily viewed as a delivery service, rather than in the role of a facilitator of competition in generation and supply, and

(ii) the historic "passive" configuration of the distribution system, in which the expectation is that virtually all the electrical energy is supplied from the transmission networks at several points in each DNO's area and is then distributed to consumers at lower voltages.

2.3 An open access based framework for distribution networks clearly needs to be developed. The Utilities Act 2000 requires DNOs to facilitate competition, and hence to open up distribution networks to provide equitable access to the energy market. In order to take full advantage of this opportunity an appropriate regulatory and commercial environment must be established and a number of technical issues related to network operation and development resolved. These are documented in the Report of the OFGEM/DTI Embedded Generation Working Group [2]. The report recognises that at present there are neither regulatory, commercial nor technical frameworks in place to encourage the DNOs to integrate this embedded generation (EG) into their systems in an optimal manner.

2.4 Broadly speaking, the major responsibilities of DNOs are (i) to maintain voltage fluctuations on the system within limits (specified by standards) and (ii) to ensure that the service quality delivered is adequate. As a consequence of the historical development of distribution systems, these responsibilities have been met by operational and development practices that involved the use of assets, facilities and resources owned and managed by DNOs. This “passive” approach to network operation considerably limits the amount of EG that can be connected and EG is effectively excluded from the opportunity to support the DNOs in carrying out their main duties.

2.5 Regulatory incentives need to be designed to encourage DNOs to consider assets and services of all networks users (such as EG) for the provision of voltage control and service quality. This would lead to unbundling of distribution network services and the development of commercial arrangements within which DNOs would carry out their responsibilities efficiently and at least cost, considering the assets and services offered by all participants.

2.6 It is expected that the majority of new renewable and CHP generation schemes are likely to be connected to distribution networks changing the traditionally passive, electricity delivery networks with unidirectional flows into active systems. In order to increase the ability of the *existing* distribution network to absorb large amounts of embedded generation (without considerable reinforcement of primary plant), active management of distribution networks may be the most economic solution. It is well known that in rural networks, the voltage rise effect is the main limiting factor for connecting embedded generation. The voltage profile in distribution networks with embedded generation can be controlled effectively within an active network environment. This would involve (i) dispatch of local generation, (ii) reactive power management and (iii) area or feeder based coordinated voltage control, including any combination of these three control strategies. Preliminary investigations [3] show that the amount of embedded generation that can be connected to an existing system can be increased for a factor of 3-5, by the use of these approaches.

2.7 In urban areas, the main limiting factor for increasing the amount of embedded generation that can be connected is increase in fault levels. A range of measures can be employed to deal with this problem, including the application of high impedance transformers, series reactors, fault current limiters and various schemes for automatic switching of the network.

2.8 The changes in the philosophy of operation of distribution networks will require closer integration of embedded generation into distribution systems. The novel application of network control and analysis facilities (e.g. advanced Distribution Management Systems) and technologies (such as Voltage Source HVDC), supported by appropriate protection and communication systems will be needed. There are many useful lessons to be learnt from experience of operating Transmission systems.

2.9 The benefits of the integration of embedded generation into distribution networks seem very significant although the costs of implementation and operation of active distribution networks have yet to be quantified accurately. Although the number of issues to be addressed is not small, and some of them are challenging, they are all tractable and the subject of extensive research and development programmes worldwide. It is now timely to demonstrate these concepts on the UK system.

2.10 In the context of security, an active distribution system should increase security of supply to local loads.

Impact on generation system operation

2.11 One important aspect of system security is associated with the ability of the system to balance demand and generation over various time scales. Large conventional generators will continue to play a central role in providing security through various services for managing the balance between load and generation (such as reserve services, load following, frequency regulation etc). However, the anticipated level of penetration of renewable generation and CHP by 2010 is not likely to make an adverse impact on the security of the national electricity system, although the cost of maintaining security will modestly increase.

2.12 The inherent intermittency of renewable generation, such as wind, will require more resources to be made available in order to manage short-term balancing between demand and supply. However the amount of additional resource required to manage the unscheduled wind power will not be on a "megawatt for megawatt" basis. The key factor here is the phenomenon of natural aggregation of individual outputs of wind farms. The output of individual wind turbines is generally not highly correlated, particularly when wind farms are located in different regions. Several studies have been recently performed that quantify the variability of wind generation over number of time horizons [4,5,6]. For example, in [4] it is indicated that for penetration of 7.3GW of wind generation ("high wind scenario"), the variability of the total wind output over 1 hour time horizons would not exceed +/- 600MW. Clearly, the present system is capable of managing this variation.

2.13 One potential issue related to balancing generation and load could arise when minimum loading (summer night load is below 20 GW) coincides with very high outputs of variable renewable generation. The proportion of large flexible plant operating on the system may be reduced considerably under these conditions. Because the fine balancing between load and generation is likely to continue to be provided by conventional plant, this situation could be dealt with by simply constraining the output from the variable generation in order to maintain security of the system. These circumstances are however likely to occur only very infrequently and detailed studies are required to quantify the cost of such operation, recognising the impact of NETA. On an annual basis, the expected economic impact is unlikely to be significant.

2.14 Although at present, large plant may be the most competitive source for providing security services, it may be important, particularly for the future development of the system, to encourage this new generation to take part in the provision of system security (e.g by load following). Currently, embedded generation is considered as negative load and not as a potentially active supplier of security, either at a system or at a local level. Embedded generation is not integrated in the system operation, in contrast to large generating units that play a vital role in providing the security of the system. A number of technical changes in the present practice of connecting and operating embedded generation may be introduced to increase the contribution of embedded generation to system security. Some overseas practices associated with the operation of embedded generation, particularly European countries such as Denmark, may be applicable in the UK electricity network. At present for example, in the UK, embedded generation is generally disconnected from the network in case of system disturbances (not only does EG not contribute to providing system security, but with its presence, it makes the management of security even more difficult). In contrast, in Denmark large offshore wind farms will be required to continue to operate during system disturbances. Note that at present, in the UK, network operators have no incentive to even connect embedded generation, while its integration into system operation is only recently being discussed. Adequate regulatory incentives will be critical in this context.

Impact on transmission system operation

2.15 The majority of new renewable and CHP embedded generation is expected to be connected to distribution networks, although large off-shore wind installations may be connected directly to the transmission network.

2.16 It does not however automatically follow that this trend will necessarily reduce the flows on the transmission network, as the location of the new sources will play an important role in determining their impact on the transmission network.

2.17 Large penetrations of renewable sources in Scotland and the North of England may contribute to an increase in the north-south power flows and may occasionally restrict the operation of conventional plant in this area. This would be dealt with by constraining-off northern generation. The costs of these constraints would be determined through the NETA Balancing Mechanism but initial indications are that the overall cost of such operation is not expected to be significant.

2.18 Furthermore, some of the old large generation plant in the north may be decommissioned anyway in the not too distant future [7], and this may therefore free some of the capacity on the North-Midlands boundary for new renewable generation.

2.19 The 18 currently proposed offshore wind farms are located mainly off the east cost of England and in the North West. These are unlikely to cause major transmission constraints.

2.20 Overall, the transmission system is not expected to be affected significantly in the short term although issues associated with stability of the electricity transmission network, i.e. transient, dynamic and voltage stability (see appendix) need to be investigated. At present, for example, it is not clear how the 18 off-shore wind farms will contribute to system stability and how sensitive this technology will be to various disturbances on the system. Detailed modelling of these schemes will have to be carried out to assess their impact on the stability of the transmission system and to specify the required generator performance.

Replacement and future development of distribution and transmission network assets

2.21 The UK distribution and transmission network was significantly expanded during the late 1950s and early 1960s and the assets then installed now approach the end of their useful life and need to be replaced.

2.22 Since privatisation of the electricity industry, distribution network owners and operators have been exposed to a spectrum of complex conflicting objectives to: reduce capital expenditure, reduce operating cost, improve reliability and service quality and offer the service at lower prices. These pressures, accompanied by the uncertain future and strong short-term objectives, have resulted in a trend to increase the life of the existing plant and to drive the assets ever harder. Furthermore, within the present regulatory climate, the asset replacement policies (transformers and distribution circuits) are primarily concerned with cost of *investment* while the cost of *losses* tends not to be given adequate consideration.

2.23 The approach of selecting network designs through minimising *life-cycle* costs of ownership and operation of the network (life-cycle costs are of course composed of cost of investment and cost of losses) has been studied at UMIST [8,9]. The preliminary results show that, in the majority of cases, low and medium voltage circuits with a five to ten- fold greater capacity than needed is more economical over 20 years – because of the reduced losses – compared to the minimum size of cable that can still carry the load. Similarly, at the transmission level, optimal loading of the circuits is between half and the third of the maximum capacity, when losses are taken into account. In their Supplementary Submission to Energy Policy Review, National Grid [4] discuss this issue from a transmission network viewpoint.

2.24 These findings suggest that the present network design and replacement strategy, which follows a minimum network investment principle, may not be optimal from an overall “UK plc” perspective particularly while the UK is making considerable efforts to reduce the environmental impact of its commerce and industry, including meeting its obligations for CO_2 reduction under the Kyoto protocols. Having in mind that losses in the UK electricity system are about 9%, comparing to Germany with losses below 5%, the potential in this area is clearly great and appropriate action is urgently required. The main concern here is whether the short term objectives of the network developers, coupled with currently inadequate regulatory incentives for investment into high efficiency distribution plant, may result in the installation of inefficient plant which will then be in operation for the next 30-40 years.

2.25 In the context of security these results suggest that the optimal design of circuits with cost of losses being taken into account is likely to meet the security requirements (driven by the minimum design recommendations P2/5) at no additional costs in a large part of the system.

2.26 It is important to stress that an efficient electricity network infrastructure may also be critical for keeping open the options for sustainable development of the UK electricity supply system. Appropriate design of circuits (based on the overall life cycle costs) leads to a strong network that is able to deal with the inevitable uncertainties in future generation, types, sizes, locations and performance.

3. Issues for beyond 2010

Operation and development of generation system

3.1 The penetration of new renewable generation is expected to continue beyond 2010. Wind and wave are expected to make a considerable contribution (say 25-30% of electrical energy), together with further penetration of CHP (say 15%) and potentially micro generation technologies (say 10%), to the development of the UK electricity system in the medium-to-long term, 2025 and beyond.

3.2 For such penetration of distributed sources it will become important that new generation technologies, accompanied by demand side management and perhaps storage facilities, take over some responsibilities from the large conventional plant for providing operational security of supply of the national system. This, in effect, would require some form of *integration* of all these sources into operation of the entire system (generation, transmission and distribution networks) including the responsibilities for system security.

3.3 Penetration of intermittent renewable resource will displace considerably the *energy* produced by large conventional plant. However, there are a number concerns in relation to the ability of this new generation to replace the *capacity* of the conventional plant and in particular its flexibility. This raises a number of questions as to whether the future sustainable system will be able to operate securely and how exactly the balance between generation and demand will be managed. The following time horizons are relevant in this context:

Seasonal balancing of supply and demand

3.4 The question here is how the potential unavailability of the renewable resource (such as wind, wave and PV) over a period of several days or weeks (particularly during a cold winter spell) would be dealt with in a system with a large contribution to overall electricity supply coming from renewable sources. As this is considered to be a plausible condition and massive load curtailments are assumed not to be acceptable, a significant amount of additional generation capacity will need to be available. The plant margin [see appendix] in such systems would have to be significantly higher than at present.

3.5 Plant with low capital and (very) high fuel cost would be appropriate for this purpose as the use of this capacity would be of limited duration and the overall operating costs are hence likely to be small. One appropriate option that satisfies the above criteria would be to keep the existing gas and/or coal conventional plant (that is due to retire due to age and/or environmental constraints) as a long-term reserve and use it in these relatively infrequent situations. Note that the additional contribution to emissions from operating this capacity would also be small.

3.6 Although not sufficient in their own right, very large bulk energy storage facilities such as the existing pump-storage, proposed DC links with Norway and Netherlands, demand side management and micro-generation may considerably reduce the amount of large conventional generating plant needed to be held in reserve to overcome such events.

3.7 Detailed studies are however required to quantify the capacity margin required, cost of such operation and the potential role of existing and new technologies.

3.8 It is important to emphasise that for this long-term reserve (generation margin) to be made available, suitable market incentives will be required. Although the current plant margin is adequate, the ability of the future system to deal with the conditions of coincidence of high demand with low output of renewable generation, will depend on the incentives to keep existing and perhaps install new generation that would run only for very limited periods. In the context of NETA, this will rely generating companies receiving very high prices in the market during the occurrences of such events. Energy prices at the time of use of this plant would have to be very high if the fixed cost of the plant is to be covered through occasional runs.

3.9 With the introduction of NETA, capacity payments to generators have been eliminated and there is no explicit reward for maintaining generation capacity. It remains to be seen if the current energy-based market mechanism will continue to provide incentives for entry of new plant and the maintenance sufficient generation margin for the future.

3.10 Correct commercial/regulatory incentives will be particularly critical if significant plant margin is required to support the operation of a UK sustainable electricity system with a very large contribution from renewable sources.

3.11 Excesses of generation (coincidence of low demand with high level of output of renewables) may require constraining off renewable generation. In addition, very large bulk energy storage (such as the existing pump storage facilities) and potentially exports through DC links may be used to manage the balance between demand and supply in these situations. However, detailed studies need to be performed to understand the level of resources (generation transmission and storage) required to maintain system security and their associated cost implications.

Daily balancing of supply and demand

3.12 At present, on a typical winter day the load increase can reach 10,000 to 12,000 MW over the morning load pickup period lasting for about 2 h. Clearly, the question here is how to manage balancing the load and generation, under such a steep increase in load, with a system with a large contribution to supply coming from intermittent sources.

3.13 The problem is complicated even further by the possibility of the output from intermittent renewables reducing during the period of the sharp increase in load. The net effect of this would be that the equivalent increase in load, seen by the system, might be considerably greater than the load pickup on its own. The extreme amounts of the net load increase would depend on the total capacity of intermittent renewables and their correlation [4,5,6] and this would need detailed studies to be performed before it is possible to quantify the implications on the system operation, amount of flexible plant required and corresponding cost.

3.14 It is considered that CHP electricity generation (large and micro) in combination with heat storage facilities could be appropriate for this task. It is envisaged that CHP generators, generally used to meet local heat demand at present, would respond to electricity demand during the load pickup. The heat generated during this period would be stored for later use. This type of combined generation and demand side management action would have to be supported by appropriate electricity pricing arrangements in order to encourage all available plant and demand, including micro generation, to take part in supporting this balancing activity. Operating the power system in this manner creates a close linkage between renewable capacity and CHP. It is assumed that the gas system will be able to respond to changes in demand for gas by CHP and other gas-fired plant but this needs to be confirmed by studies.

3.15 Finally, it is considered that HVDC links, together with pump storage facilities and demand side management actions may also be used for this purpose. Of course, in the case international HVDC links, the operators in neighbouring countries will use pricing signals to make decisions about the profitability of managing of the UK morning load pickup.

3.16 Detailed studies need to be performed to quantify the amount of flexibility that is likely to be required under different development scenarios to meet such large changes in demand and preserve system security under such conditions. Studies are also required to quantify costs associated with the various options and values of alternative technologies that can be used for this purpose.

Regulation in real time

3.17 Unscheduled loads and generation within a time horizon of half hour are managed by dispatching generation resources participating in the balancing mechanism. Once every several minutes, the system operator moves generation up and down to follow changes in load and unscheduled generator outputs. These resources are often called load following ancillary services.

3.18 In order to manage the balance between load and generation on a minute-by-minute basis, automatic generator control systems are used.

3.19 It is important to emphasise that the correlation of output between intermittent generators will be relatively small in these time scales, and their combined output will be reasonably smooth. The amount of the mismatch between generation and demand that would need to be managed would be relatively modest. The task of real-time balancing of the system might be carried out effectively through using combination of storage facilities, such as pump-storage at Dinorwig or new generation of fuel-cell type storage, demand side management and by modulating the output of renewables (wind). Again, detailed studies are required to quantify the amount of regulation services required and their cost.

3.20 For management of sudden losses of generation (forced outages of generating units), automatic frequency regulation systems are used that control the output of generators and/or trigger demand reductions. The amount of these fast frequency response services required will depend on the size of the loss to be compensated and the amount of directly connected rotating plant (inertia). In this context, the operation of generation that is connected through simple power electronic interfaces (such as PV) will generally increase the amount of response services required [10].

3.21 Detailed studies are required to assess the amount of very flexible plant that may be required to manage intra-half hourly, minute-by-minute load-generation imbalances as well as sudden losses of generation and loads, under different generation development scenarios.

3.22 In order to ensure that sufficient amount of flexible plant is available, flexibility should be encouraged and such plant should be appropriately compensated through market and regulatory mechanisms. At present, there are no strong incentives to install flexible plant, particularly in the case of embedded generation. This trend would have to be reversed, and the majority of generation would need to be able to contribute to maintaining system security if a sustainable power system is to be developed. (Note that NETA does not directly incentivise plant flexibility, but only output predictability).

Impact on transmission

3.23 If the massive resource of renewable generation in the form of off-shore wind and wave power available to the UK is to be exploited, an adequate transmission network will become critically important.

3.24 In this case, the transmission network will continue to play an important role in providing security of supply and facilitate the development of the UK sustainable power system.

3.25 Exploitation of marine energy, will involve the development of new systems for collecting electrical energy from large marine energy systems and its transmission to shore. Furthermore, the question as to what reinforcements on the existing transmission network would be needed in order to for this power to be than transported further, requires detailed studies. This may involve solutions similar to one discussed recently regarding the application of undersea link along the west coast.

3.26 It may be recalled the national transmission network was developed to link large power stations in coal mining areas with cities and towns in the South-East and Midlands. Although the existing conventional generating plant may remain to be used in the form of long-term reserve (see sections 3.4-3.11), there is a legitimate question as to how adequate the present system is going to be in the context of possible future developments in generation and what additional reinforcements may be required.

3.27 Furthermore, some of the transmission circuits may prove not to be very useful once large conventional generating assets are decommissioned. However, there may be ways to increase the utilisation of such circuits and detailed technical and economic assessment of the options will be required to be carried out.

3.28 Similarly, the development of interconnectors, such as the proposed scheme to link the NGC system with Norway and Netherlands via DC links, will also contribute to enhancing system security and diversity of supply.

3.29 Issues associated with stability of the electricity transmission network, i.e. transient, dynamic and voltage stability (see appendix), would need to be re-examined for various development scenarios and associated generation technologies.

3.30 The issue of financing and charging for transmission reinforcements and developments, and in particular interconnectors, has recently received considerable attention by academia, regulatory agencies and industry. Two main approaches have been identified, namely the merchant versus the regulated approach to transmission expansion [11], which is also debated within the PIU energy review [4]. One of the main issues associated with this debate is related to the development of a stable regulatory framework, which would minimise the risk of investment.

3.31 A strong transmission network will be important for keeping open the options for future development of the generation system. However, a very large-scale penetration of small-scale generation (millions of units) may considerably reduce the amount of energy transported over the transmission network and decrease the importance of transmission in maintaining system security.

Impact on distribution

3.32 As discussed in Sections 2.1-2.10, distribution networks of the future are likely to be managed actively with considerable amounts of computer, communication and control technologies applied to manage physical flows on the network as well as the flows of information between various devices controlling the behaviour of the plant and equipment.

3.33 As the penetration of embedded generation increases, distribution network operators will have to take more responsibilities for the provision of security related services. This would be a new task which distribution network operators would need to conduct. This will be necessary if various forms of embedded generation are to be integrated in the operation and development of the entire system in order to ensure its secure operation and adequate service quality.

3.34 It can be observed that in case of the installation of very large off-shore generation schemes, operation of distribution networks may not be very much affected. However, the development in micro-generation may have a considerable impact on distribution networks.

3.35 In the last few years advances in technology have substantially reduced the cost of micro-generation so that, in due course, this form of generation may be more widely used.

3.36 Such development could potentially challenge the fundamental paradigm of central management of system security. Clearly, with a very large penetration of small-scale generation (millions of various units), i.e., with the increased number of independent decision-making entities, a radical change from the central to a distributed management of the entire system operation will be required. This technical challenge will, in turn, impose serious questions as to what market and commercial arrangements are needed to manage the balance between demand and supply in a system composed of millions of small generators and what regulatory approaches would facilitate evolution of the system from its present to its future form.

3.37 Integration of this generation into system operation and development could be carried out thorough interconnecting small modular generation sources to low voltage distribution systems forming a new type of power system, known as the Micro-Grid. Although the main issues associated with technical, regulatory and commercial requirements for the operation of such systems and their economics are being identified, adequate solutions are still very much in the research domain.

3.38 Ultimately, the development of micro-generation will reduce the importance of network security. In a sense, system security as an issue may disappear due to the presence of massive number of small generators distributed across the country (failures of a small number of such devices would not threaten system security).

Conclusions

4.1 There is no doubt that maintaining the current level of system security with a generation mix containing significant renewable generation will become more difficult. However it is believed that all the issues discussed above can be addressed by technically feasible engineering approaches within reasonable economic constraints. Clearly detailed studies will be required and the commercial incentives to integrate the operation of the networks and the embedded generation are crucial.

4.2 For the 2010 targets the main priority will be to *integrate* the operation of embedded generation and *distribution networks* and no significant issues related to system security are likely to emerge. A large proportion of costs of accommodating this generation into the UK electricity system will be associated with integration into distribution networks. The present generation system has the flexibility to balance supply and demand with this level of new renewable generation and CHP. The present transmission system appears adequate to accommodate the expected new generation.

4.3 In the medium-to-long term, with a considerably larger contribution of electrical energy supplied from various forms of embedded generation, and in particular with the application of large-scale intermittent renewable source, maintenance of system security will require *integration* of this generation in the operation and development of the *entire* system. Balancing demand and generation will be a matter of primary importance and a considerably increased generation margin will be required to deal with intermittency of the new renewable generation. The new generation (together with storage [12], DSM etc) would have to assume responsibility for security through flexible operation. Incentives for maintaining generation capacity and flexibility would need to be developed.

4.4 Strong and efficient transmission and distribution networks offer the important advantages of contributing to network security, reducing network losses, facilitating competition and managing the inevitable uncertainty in the types, locations, sizes and performance of the future generation.

Appendix: An overview of electricity system security

A1. Introduction

1.1 The term “Network Security” is used to describe all aspects of security of the electrical power system and is used to distinguish these technical issues from fuel security or Security of Supply. This report uses the terms system security and network security interchangeably and assumes they have the same meaning.

1.2 An overriding factor of the operation of power systems is the need (desire) to maintain system security. It is well known that a widespread system blackout is extremely damaging for society and leads to very high costs. This is why system security is of paramount importance. Broadly, security means providing customers with a supply of electricity which is continuous and is of the defined quality (frequency and voltage). System security involves operational and design practices including appropriate levels of reserves necessary to keep the system operating under various disturbances in the generation, transmission and distribution segments of the system. This requires that generation, transmission and distribution systems must have sufficient reserves and flexibility to maintain supplies under conditions of plant failure.

1.3 Generally, security at the *system level* is associated with the ability of the system to follow changes in load (achieved by flexible generating plant) and reserve and response capability necessary to react to disturbances caused by faults on both generation and transmission facilities. Services related to maintaining system security are provided through a mix of compulsory services (such as frequency response and reactive support) defined by the Grid Code, and a spectrum of commercial services (such as standing reserve). All are essential for maintaining system integrity.

1.4 The ability of embedded generation to support continuity of supply following failures in distribution networks is referred to *local* security. This aspect is however not very relevant for the overall integrity of the system.

1.5 Security standards define the events (called credible contingencies) that the system must be able to withstand and then continue to operate satisfactorily. Quality standards define allowable fluctuations of voltage and frequency around their respective declared values (frequency must not vary for more than +/-1% while voltage must be within +/-6% for voltages below 132kV and +/-10% for voltages at 132kV and above).

1.6 While adequate generation capacity is a function of market forces, transmission and distribution networks are planned and operated in accordance with security standards laid down in the licences of the operating companies.

A.2 Generation system security

The central question for the security of generation systems is to balance demand and generation over a time horizon from a second, over an hour and a day (operational time scales), to months or years.

Plant margin [7]

2.1 The former Central Electricity Generating Board (CEGB) worked on the assumption that only about 85% of the total installed generating capacity would be available during winter peak demands. In other words, it was necessary to meet 100% of demand with only 85% of installed generation. Furthermore, additional generating capacity was required to cover the risk that the weather might be colder than expected. Therefore, while planning their generation system, the CEGB required a 24% plant margin (some large utilities work with a 30% margin) to deal with such eventualities. With this margin, demand disconnections were expected occur in not more than 9 winters in hundred years.

2.2 It is important to stress that this margin of generating plant over peak demand was necessary for achieving the desired level of security of electricity supply (according to CEGB generation planning standards) and should not be considered as surplus in generation capacity. This level of generation margin was economically justified by balancing the cost of this capacity margin against the cost incurred by consumers of electricity (society) in cases of interruptions caused by shortages in generation.

2.3 In market based operation of the electricity system, there is no set standard for the generation planning margin and the need for new plant is determined by market forces.

2.4 Although the amount of generation available to meet expected demand at any point in time is to be determined by market forces, it is important to consider how a power system with a large penetration of renewable energy sources would deal with large seasonal and daily variations in demand and how a sufficient amount of capacity margin will be maintained.

Balancing of generation and demand in the operation timescale

2.5 Fluctuations in frequency are the direct measure of the balance between demand and generation in an AC power system. Frequency falls below 50 Hz when demand is greater than generation and rises above 50 Hz when generation is greater than demand. For the system to operate satisfactorily, the frequency must be maintained continuously within narrow limits around 50Hz. As indicated above, quality standards specify the allowable deviations of the frequency around the declared value for various situations [7].

2.6 In the time horizon of about one to a few hours, the balance between demand and generation is managed by forecasting demand and then scheduling appropriate generation. This is a demanding task as on typical winter day the load increase can reach 12,000MW over the morning load pickup period lasting for about 2 hours. Maintaining the load/generation balance and hence frequency is achieved by coordinating flexible output of large coal and gas plant with pump storage facilities providing fine control (the demand has not been historically controllable and so the balance is achieved by adjustments at generation sides). This could be a challenge for a power system with a large contribution of various embedded generation technologies, particularly intermittent renewables.

2.7 In the time horizon of less than a minute, frequency is controlled automatically through systems that control the output of generators and/or trigger demand reductions. The service required is divided into two categories of control, continuous and occasional [13]. The frequency service for continuous control (load following) is primarily provided by central generators equipped with appropriate governing systems that control their outputs to neutralise frequency fluctuations as a result of relatively slow changes in demand and generation.

2.8 The occasional control service is required for the management of system frequency after a sudden loss of generation and is provided by both generating plant and load reductions from some industrial customers. This includes frequency response services provided by instantaneous increase in generation or reductions in loads required to minimise the initial frequency drop. In order to bring the frequency back to normal, the operator then calls upon reserves, provided by generators and some demand that can change their outputs relatively quickly. Similarly to the above, there is a question as to how embedded generation and demand side management could make a contribution to providing such service in the power systems of the future.

A.3 Security of the transmission system

3.1 The Transmission system plays a vital role in providing security of supply as the outages (non-availability) of generation in a particular location can be overcome by transporting energy from other remote generators and hence ensuring continuity of supply.

3.2 The level of required security provided by the transmission network is defined by S*ecurity Standards (*planning and operating) which, broadly speaking, define a set of events that the transmission system must be able to withstand. For example, a so-called “N-1 security standard” would require the system to work satisfactorily following a loss of any *one* of its N elements. NGC’s operating standard requires the system to continue to operate following the loss of any double circuit lines (two transmission circuits on a single tower) and certain high-risk pairs of circuits. In order to achieve this, the loading on the transmission system under normal operating conditions must be limited to levels that permit any credible contingency to occur without causing power quality limits (specified by a standard), component (circuit) or system limits to be violated. It could be interpreted that about 60% of the total NGC transmission assets are installed for reasons of security.

Voltage Quality standards

3.3 In the context of transmission, the quality standard specifies the allowable fluctuations of voltage around nominal values for various voltage levels for both operation and planning time horizons. This standard imposes the requirement for sufficient voltage control capability to be available to the system operator. This service is provided by both transmission facilities and generation facilities.

Circuit and system limitations

3.4 Circuit limitations are associated with the thermal capacity of the circuit elements. Power flow in a transmission line heats the conductors and, if overloaded may permanently damage the conductors or affect safety by causing them to sag excessively.

3.5 System limitations are determined by the arrangement of the individual circuits in the network, their individual limitations and the behaviour of the system as a result of disturbances. These are usually divided in three categories:

3.7 *Transient stability* phenomena occur due to a short circuit (fault) on a transmission circuit over a period of a fraction of a second to several seconds. Some generators accelerate and others decelerate so that it may not be possible to restore the generators to synchronous operation after the fault is cleared. With generators running at different speeds, power flows erratically over the transmission system causing its protection systems to operate and causing the system to break up into separate sections, with more or less generation than respective loads. In order to ensure transient stability, limits are placed on the amount of power that may be transmitted from one area to another. These are referred to as transient stability limits.

3.8 *Dynamic (in)stability* phenomena occur over longer periods than transient stability, up to several minutes. They are caused by spontaneous oscillations in the systems that may occur when transporting large amounts of power over long transmission circuits. Dynamic instability is often prevented by imposing limits on the levels of power transfer between specific areas. This has been an issue on the interconnector between Scotland and England.

3.9 *Voltage instability**:*** It is necessary to ensure that system voltage will not collapse due to faults or other disturbances on the system, or to inherent instability of the voltage maintenance process. Voltage collapse may occur in a matter of seconds, if the contingency is severe, or it can occur through a gradual decline of voltage over a period of many minutes. Wide-area system collapses that have been experienced over that last few decades, particularly in the US, Canada, Japan, France have been caused by voltage instabilities. The vulnerability of the system to voltage instability is complex and determined by the characteristics of the network, generation and load patters and the operating procedures used. Adequate reactive power margins, provided by large generators or compensating plant at key locations, are important for avoiding voltage stability problems. Over the last several years NGC has installed a considerable amount of reactive support in Southwest and Midlands areas in order to enhance stability of the systems.

A.4 Distribution networks and system security

4.1 Distribution networks have historically provided security to local loads and problems in the distribution network have not affected security of the entire system. Recent debate has been focused on the way embedded generation is treated within Engineering Recommendation P2/5 (security standard) that specify the contribution that embedded generation makes in the context of local security and its ability to substitute distribution network assets and/or contribute to service quality seen by the end customers [14]. This is however not directly relevant to the overall integrity of the national electricity system.

4.2 With increased penetration of embedded generation it may be desirable to enable this generation to take part in providing system security services, which may require changes in the present philosophy of operation of generation embedded in distribution network

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