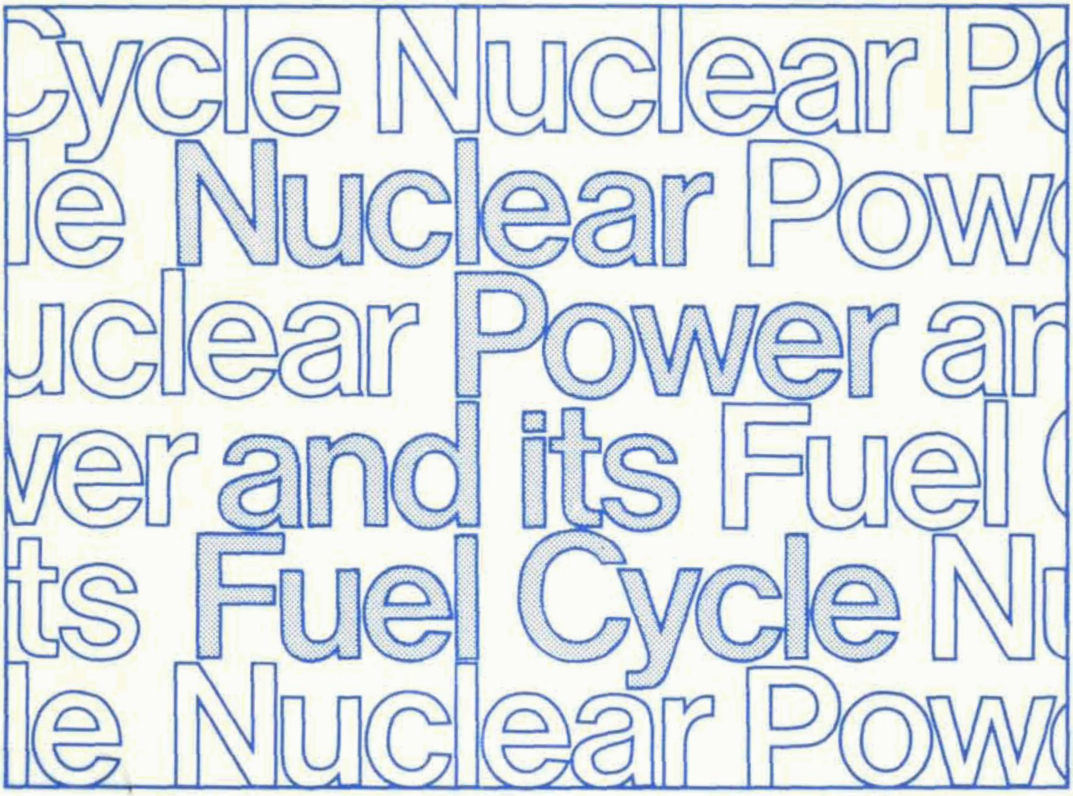

TECHNICAL REPORTS SERIES No. 271

Introducing Nuclear Power Plants into Electrical Power Systems of Limited Capacity: Problems and Remedial Measures

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1987

INTRODUCING NUCLEAR POWER PLANTS INTO ELECTRICAL POWER SYTEMS OF LIMITED CAPACITY: PROBLEMS AND REMEDIAL MEASURES

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FOREWORD

The presently proven nuclear power plants (NPPs) have been developed for use in large interconnected power systems of high quality and hence are likely to face problems when introduced into grids where this quality does not exist. An effort is now being made to gain a precise understanding of these problems and to derive suitable means for mitigating them.

The major causes of poor grid voltage and frequency stability include:

- insufficient generation and interconnection
- lack of sufficient control equipment and inadequate load dispatching
- poor reliability of protective systems
- non-optimum operations management and lack of co-ordination between connected utility organizations.

While improvements in systems control and better co-ordination of protective functions are presently being given highest priority and satisfactory results may be expected in a reasonable time, the inadequacy of generation and interconnection is likely to persist for a much longer period owing to the high capital requirements involved in making improvements. This means that the failure of a large generating unit or an important tie line would continue to cause severe transients in networks of limited quality. The network survival during such transients might impose exacting demands on NPP performance and could lead to loss of off-site power supply to NPP auxiliaries.

An earlier guidebook published by the IAEA as Technical Reports Series No. 224, ''Interaction of Grid Characteristics with Design and Performance of Nuclear Power Plants: A Guidebook'', has created a definite awareness of the problems inherent in operating NPPs within an electric grid of limited performance and indicated some directions where efforts to mitigate the various problems could be fruitful. It has now been felt desirable to expand the scope of the assistance in this area by providing more prescriptive guidance on the necessary steps for the safe and economic incorporation of NPPs into weak grids.

To this effect an Advisory Group composed of experts from eight countries met in Vienna with the aim of assisting the Agency in preparing guidance. The present publication, which represents the results of the work of the Group, provides an in-depth treatment of the special technical issues associated with grid–NPP interactions and is expected to assist the safe and economic operation of NPPs in electric grids of limited capacity.

The Guidebook will be mainly directed to utilities in developing countries which will have to establish the specifications of the NPP they desire to introduce into their grids. It is also expected to provide information feedback to NPP designers and manufacturers.

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EXECUTIVE SUMMARY

The performance record of nuclear power plants (NPPs) operating in the developed countries during the last two decades and the demonstrated economic competitiveness of nuclear energy in several developed countries have suggested that nuclear energy may be a viable alternative to the conventional non-renewable energy sources in satisfying the electrical energy needs of the near future. Several NPPs of standardized unit capacities and of different types with proven performance in the well regulated, large interconnected power systems of the developed world are commercially available. There exists a strong incentive to consider the introduction of such standard NPPs to meet the fast growing electrical energy requirements in the industrially developing countries. In this regard, it becomes necessary for the developing countries to take a close look at the features of their existing power systems, the design and operating characteristics of NPPs and problems of compatibility between the two before the introduction of NPPs. The present guidebook is an attempt to describe the necessary steps for ensuring such mutual compatibility and a safe and economic incorporation of NPPs into the power systems of the developing countries.

GRID CONDITIONS IN THE TWO 'WORLDS'

NPPs of unit capacities of up to 1300 MW(e) have been successfully integrated into the well developed grids of industrialized nations, whereas NPPs of only 220 MW(e) have faced severe problems during operation in the weak and poorly regulated grids of the developing countries. The contrast between the grids in countries at two different stages of development (as would be evident from the data relating to the characteristics of a high performance grid in Appendix I and those of a low performance grid given in Appendix II) is responsible to a large extent for the difference in the performance level of NPPs in the two types of countries.

The high performance grids that have brought about progressive developments in the design of NPPs and their control systems can be characterized as follows.

- A large total installed capacity of the power system, often more than ten times the size of the largest generating unit.
- A high degree of network interconnection.
- A sufficient amount of spinning reserve and total operating reserve.
- Automatic control of generation to achieve a fine regulation of frequency.
- Sufficient capacity of reactive compensators and automatic controls for maintaining satisfactory voltages at all nodes of the network.
- Reliable high speed protective systems with system-wide co-ordination of relaying schemes.

- High stiffness of the grid; that is, the drop in frequency following forced outage of a generating unit is low (in most cases a drop of less than 1 Hz following loss of the largest unit without the action of system emergency controls).
- A low rate of drop of frequency for loss of generation, making the duties of control easier.
- The existence of well planned emergency control measures such as load shedding and restoration during occurrences of serious generation–load imbalances, though these are very rare.
- An efficient means for communication and co-ordination between generating stations and load dispatch centres.
- Advanced system controls and operating strategies achieving a high degree of system security.
- Finally, as a result of the foregoing, high reliability and quality of power supply at most parts of the power system.

The developed countries having grids with such characteristics were already increasing their generating capacities with large base load thermal stations, exploiting the economies of scale these afforded. Large NPPs fitted this scheme well, and the successful NPPs were standardized in unit sizes of 440 MW(e) and above.

There is a tendency to adopt NPPs of large unit size, with similar economic advantages, to satisfy the increasing load demands in the developing countries. However, the introduction of a large NPP unit in an existing weak grid, unless accompanied by measures to improve grid performance (requiring considerable investments), may jeopardize the safe and economic operation of the NPP and the power system itself. Limited experience with operating NPPs connected to weak grids has made this point amply clear.

The infrastructure and capital outlay required to attain all the cited characteristics and reliability standards of high performance grids may not be within the immediate reach of most developing countries. The present electric power systems in these countries are generally characterized by a low reliability of supply and unstable voltage and frequency caused by one or more of the following:

- insufficient generation and interconnection;
- inadequate automatic controls and the lack of efficient load dispatch centres with telemetry and good communication systems;
- poor reliability of protective systems;
- non-optimum operations management and poor co-ordination between related organizations.

Improvements in system controls and better co-ordination of protective functions are currently receiving the most attention from the utility managements, and may be satisfactorily made in a reasonable time. However, the inadequacy of generation and interconnection is likely to persist for much longer owing to their high capital requirements. Thus the possibility of failure of a large generating unit or of an important tie line would continue to cause severe transients in the network. Network survival during such transients might impose exacting demands on the performance of NPPs introduced, and at times may lead to loss of off-site power to NPP auxiliaries, raising issues of NPP safety. The rational approach to introducing NPPs to augment the generating capacity of such power systems would therefore be to ensure in advance that a well co-ordinated grid control system (including automatic load shedding) can manage all likely disturbances in a manner that minimizes the chances of NPPs tripping and provides reliable off-site power of satisfactory quality to the NPP when it is shut down.

NPP CHARACTERISTICS AND THEIR OPERATIONAL FLEXIBILITY IN WEAK GRIDS

The characteristics of the NPPs need to be scrutinized with reference to the conditions generally expected in weak grids of low performance. The widely used standard designs of pressurized water reactors (PWRs), boiling water reactors (BWRs) and CANDU pressurized heavy water reactors (PHWRs), their inherent response characteristics and the plant controls employed with them constitute the subject matter for the present effort towards NPP evaluation.

OUTAGES FOR REFUELLING

PWRs and BWRs using enriched uranium fuel and ordinary water as moderator and coolant need to be refuelled after every 12 to 18 months of operation, requiring a shutdown period of 4 to 8 weeks. Major maintenance work can also be undertaken during this period. PHWRs using natural uranium as fuel and heavy water as moderator and coolant operate with on-power fuelling on a daily basis, permiting more flexibility in scheduling annual maintenance shutdowns. These scheduled NPP outages have to be considered in overall maintenance planning for the power system so as to assure satisfactory reserve margins at all times for system operation.

TIME LOST DUE TO FORCED OUTAGES

Since the forced outages of NPPs can be relatively more frequent in weak grids, the time taken by these NPPs to come back to full power after load rejection, trip or shutdown becomes an important factor in system operation. While satisfying constraints on power ramping in the reactor, turbine loading rate, etc., PWRs and

BWRs can be brought to full power from the hot tripped condition in 5 to 6 hours, while raising the power level to around 70% is possible within 30 to 45 minutes in the case of a PHWR. However, if the PHWR cannot be brought back up to at least 65% of full power within 30 to 45 minutes after reactor trip, the excessive buildup of xenon will prevent the reactor from going critical for the next 36 hours. The time for all NPPs to reach full power starting from cold conditions will be longer. However, for LWRs, it may take up to 3 weeks to reach full power for the first time after refuelling owing to the waiting period required for conditioning the fuel.

DYNAMIC RESPONSE OF NSSS

The inherent dynamic response of the nuclear steam supply system (NSSS) (the reactor and the steam generator) to changes in the amount of steam drawn depends critically on the values of the reactivity coefficients as well as the thermal time constants involved in various elements of the reactor and the steam generator. Since PWRs have significant negative reactivity coefficients at coolant-moderator temperatures, increased steam supply through a reduction in the steam generator pressure and the primary coolant temperature causes an increase in reactor power. This imparts a self-regulating characteristic to PWRs. In the BWR, with a large negative value for the coolant void coefficient, any increase in the amount of steam drawn causes a decrease in reactor pressure and increased voiding in the core, leading to a reduction in reactor power. Hence the inherently unstable BWR must be made to follow load changes only by the action of a reactor control system receiving input signals based on the desired plant load. Since the coolant temperature coefficient of reactivity is negligible in PHWRs, load following by the reactor may only be achieved through suitable reactor control systems.

NPP CONTROLS TO MEET CHANGING LOADS

Though it is preferable to operate NPPs in the base load mode, the frequency fluctuations in weak grids would often cross the governor dead band, causing transient changes in the opening of the turbine throttle valve. The plant control systems of PWRs and PHWRs should be designed to keep the steam pressure, the water level in the steam generator, the primary coolant temperature and pressure and the reactor power transients following such a frequency change within specified limits, and to effect the desired change in reactor power if the plant is in the frequency control mode. The regulation of PWR power to correspond to the set point for the turbine power is achieved by the reactor control system acting on the control rods to maintain the average temperature of the primary coolant at the programmed value. Frequent swings in frequency will therefore be reflected in swings in reactor power, as well as changes in the local distribution of core flux in the vicinity of the moving control rods. The base load operating PHWRs (while operating in the turbine-follow-reactor mode), on the other hand, have their reactor power regulated independently around the value set by the operator. The changes in the throttle opening due to governor action following grid frequency fluctuations are only temporary, since the pressure control system for the steam generator will restore the throttle position to make the turbine power equal to the heat supplied by the reactor to the steam generator during all steady states. The reactor power is not changed because of such steam flow changes. The frequent movements of the throttle valve due to fluctuating grid frequency can generate severe transients, particularly in the primary coolant pressure, which needs to be maintained within trip limits by a pressure control system of high performance.

In BWRs, the turbine acts as a slave to the reactor, and the throttle valve opening is adjusted to match the reactor power so that the pressure in the reactor vessel is maintained within close limits. The reactor power in the range of 60% to 100% is controlled by varying the recirculation flow, while in the lower range this is effected by the movement of control rods. With control of the recirculation flow through thyristor based pump drives of variable frequency, the power variation can be as much as 20% per minute, while with the control rod action the manoeuvring rate is restricted to 1% to 2% per minute. While the grid frequency is being controlled, the reactor power set point is adjusted by frequency deviations and the contribution of the NPP towards correcting the error in the grid frequency appears with a short response time. In the base load operating mode, BWRs are kept immune to all frequency fluctuations.

If any of these NPPs were to face conditions of partial or total load rejection, the turbine power and the amount of steam drawn would suddenly fall, causing a serious energy imbalance in the steam generator/reactor until the reactor power is reduced to match the turbine demand. In order to manage the pressure transients in the steam and the primary coolant during such a situation, the excess energy must be released by disposing of excess steam into the condenser and to the atmosphere by the automatic opening of bypass valves, whose speed of response should match that of the throttle valve. The reactor power is subsequently brought down at a slower rate. Reactor power run-back due to such reasons external to the plant or due to internal plant problems is achieved by inserting control rods or by adjusting the recirculation flow (BWRs only), and step reduction, when necessary, is effected through a partial scram, by the fast insertion of a group of control rods. Since incidents such as net load rejection, generator trip or turbine trip are likely to be more frequent in a weak grid, it is important that the control systems of the NPP be designed to withstand these large disturbances reliably without causing a reactor trip and consequent plant unavailability. Further, if the reactor trips after severance of its link with the grid, total loss of Class IV supply becomes inevitable.

FREQUENCY AND VOLTAGE LIMITS OF OPERATION

NPP vendors recommend normal operation of the plant in the frequency band of 98% to 100.5% of nominal and with a generator terminal voltage in the range of 95% to 105% of nominal. Operation beyond these limits is restricted to short periods or reduced power, or both. Since prolonged operation off nominal frequency is detrimental to the life of turbine blades, the NPP must be isolated from the grid during conditions of severe underfrequency or overfrequency. Since variations in frequency, as well as in voltage, over large ranges are likely during the frequently disturbed conditions of the weak grid, it is necessary to ensure the reliable operation of NPP auxiliaries without tripping due to power supply transients. Tripping of important auxiliaries may lead to tripping of the unit, producing further aggravation of the problem. This factor should be considered during the selection of auxiliary motors and the design of their protection schemes, etc.

LOAD FOLLOWING CAPABILITY

Though the preferred mode of NPP operation in all grids is a base load mode, when the nuclear generation exceeds the minimum load demand in the grid (either owing to the very large number of NPPs introduced, as in some developed countries, or owing to the operation of an NPP in a small islanded part of a weak grid) the NPPs are required to perform a load following operation. Decreasing power from the NPP following load reduction is not a serious problem, since excess steam can be bypassed into the condenser immediately after the load change and the reactor power can subsequently adjust slowly. Increasing output from the NPP is constrained, however, by its available spinning reserve and dynamic response time, as well as its permissible power ramping rate.

Steam generators in PWRs are operated with programmed steam pressures that decrease with increasing reactor power during all steady states. Some of the fast spinning reserve available from the PWRs can thus be used to meet a sudden increase in grid demand during which the turbine power picks up fast by governor action. BWRs and CANDU PHWRs are designed to operate at constant reactor/steam generator pressures and do not provide such reserves of stored energy. While the initial extra energy is supplied to the turbine during the reduction of the programmed pressure in the steam generator, further energy matching is achieved by changes in reactor power through the action of reactor control systems. In PWRs the control system is aided by the inherent load regulation characteristic. Continuous raising of the reactor power for PWRs is constrained by the limitations imposed on control rod movement due to the associated distortion of the axial profile of the core flux, which, if excessive, can lead to fuel failure caused by hot spots. For these reasons, it is reported that PWRs can withstand a step load change of 10% followed by ramping rates of up to 5% per minute after an interval of about five minutes. CANDU PHWRs permit a normal ramping rate of 12% per minute but even higher rates (60% per minute) are possible to meet emergency needs, subject to constraints on the turbine loading rate. The additional constraint on PHWR operation due to xenon poisoning does not permit reactor power reduction in excess of 35% from high power operating levels. Smooth load following operation within this range is again critically dependent upon the response of control systems for the steam generator pressure, the primary coolant pressure and the reactor power, and the co-ordination between these systems to maintain all transients within set-back or trip limits.

BWRs respond to changes in the load demand by varying the reactor power through control of the recirculation flow at rates as high as 20% per minute. However, if the reactor power is low (less than 60% of nominal power, or just below the control range for the recirculation flow), the loading rate comes down significantly (by 1% to 2% per minute). Since the grid frequency signal directly controls the reactor power, the change in turbine power follows the demand change with time constants of around 15 to 20 seconds. The above maximum load pick-up rates are further constrained by the stress induced in other sensitive components of the NPP, particularly the turbines. Many turbine manufacturers suggest a maximum loading rate of 5% to 10% per minute.

EFFECTS OF CYCLIC STRESSES

Frequent disturbances originating in weak grids induce temperature and pressure transients in various NPP processes, resulting in thermal and mechanical stresses in certain plant components. The transient stresses due to major disturbances such as full load rejection, islanding or unit trip, together with cyclic stresses caused by small but continuous disturbances, may lead to a reduction in the life of components. The torsional stresses induced in turbine shafts by abrupt changes in the turbine load during load rejection or due to grid faults and their subsequent clearing are known to have damaging effects leading to fatigue failures.

RELIABILITY OF THE PROTECTION SYSTEM

The frequency and duration of unsafe situations for reactors in weak grids are much greater than those in the environment of high performance grids, i.e. the statistics for various initiating events (such as loss of power) leading to unsafe reactor conditions (loss of primary coolant) show that they occur more frequently. If the probability of a failure to shut down the reactor during an unsafe situation is to be kept at the same low level (less than one in a million), the reliability of the protective system hardware of NPPs in weak grids may require enhancement.

ON-SITE POWER SUPPLIES

Total loss of power or a station blackout condition at an NPP site is likely to occur with a significant frequency given the inadequacies of weak grids and their controls. An NPP trip during or following a house loading operation, grid collapse following an NPP trip, or grid supply failure during shutdown of an NPP will all lead to a total loss of Class IV supply, in which case the safe maintenance of the reactor in the shutdown condition must be managed using the on-site emergency electric power system (EPS) only, which is of limited capacity. The EPS consists of diesel generators and battery banks. The diesel units have sufficient capacity to drive the pumps for primary core cooling during shutdown and other important auxiliaries necessary to ensure station safety. The battery banks and uninterruptible AC supplies connected to them provide the necessary power to the instrumentation and control systems. Since loss of off-site power has a much higher probability in weak grids than in high performance grids, a much greater reliability of the on-site power system may be required in order to keep the probability of the simultaneous failure of both off-site and on-site supply at the same low level.

INTEGRATION OF THE NPP WITH THE GRID

Any electrical generating unit connected to a power system must continually interact with that system. Although well developed power systems are never in a completely quiescent state, most of the interactions due to normal fluctuations in loads or system conditions do not constitute changes of a significant magnitude. However, the range of voltage and frequency variations in weak grids, even under 'normal' operating conditions, can be fairly large. In this context the proper assessment of grid characteristics becomes the necessary first step towards the selection of an appropriate NPP and its successful integration with the grid.

ASSESSMENT OF GRID CHARACTERISTICS

The planning for an increase in generating capacity by way of an NPP precedes the commercial operation of the NPP by a significant period (about ten years). The projected conditions of power system operation during the lifetime of an NPP are based upon a statistical and to some extent a heuristic understanding of the existing system performance and commitments, as well as plans for development in related areas. The operational performance of the existing power system must be monitored over a reasonable period of time, with the aim of obtaining reliable estimates for:

- daily, weekly and monthly load variation;
- the magnitudes and frequencies of random load variations;
- the frequency variations during normal system operation, i.e. without any major disturbances such as generation losses, line losses or faults;
- voltage variations at selected points, particularly at the proposed connection point of the NPP;
- the power flow through the tie lines;
- the frequency of transmission line faults;
- the voltage, frequency and tie line flow oscillations after faults;
- the speed and reliability of protective systems;
- the frequency of forced outages of generating units;
- the frequency of severance of the interconnection with neighbouring systems;
- the frequency and voltage swings following generator or line outage, particularly the initial rate of frequency drop, the lowest frequency reached and the time for recovery;
- the frequency of the load shedding operation to manage shortages;
- the frequency of line outages leading to the formation of islands within the grid;
- the frequency and duration of grid collapses, if any.

These data will give a picture of the frequency and magnitude of probable disturbances in the grid. They will also bring out the inadequacies in the existing system design, the speed of response of the generating units and their controls, the reliability of protection and load shedding schemes, etc. With the current operational data as guidance, simulation studies of the performance of the power system during all conceivable contingency conditions would help in obtaining a reasonably realistic assessment of the grid performance during the projected period. Such simulation studies would require many data regarding the grid network, loads, generating units and their control systems. While inherent characteristics of individual items of equipment may be provided by the manufacturer, most system characteristics will have to be identified from recordings of important parameters during both normal operation and disturbed conditions. Special tests may be necessary for the reliable identification of some important parameters, and these tests should be performed wherever possible without causing serious upset conditions in the grid.

Over the entire range of operating conditions expected, load flow studies should be performed to predict system requirements for satisfactory steady state operation. Necessary remedial measures should be taken for any undesirable conditions detected, such as a poor voltage profile or tie line overloading. The usual transient stability analysis for periods of up to 5 seconds following major disturbances would reveal problems due to loss of synchronism between any of the generating units. In order to obtain the dynamic response of the system over extended periods (up to 30 seconds), studies must be carried out with suitable models representing the generator excitation controls, the power system control and protective systems, including the load shedding relays, the turbine controls and the boiler response. Such studies will reveal the systems behaviour following loss of a large amount of generating capacity or of interconnection. Also, the inadequacies in the existing controls may be brought to light and suitable remedial measures may be implemented. The contribution of the NPP in handling such power system disturbances, as well as the effect of these disturbances on the NPP and its auxiliaries, can best be assessed by including an adequately detailed dynamic model of the standard NPPs during these studies. The results of these studies can have a strong influence on the selection of the size and type of NPP for incorporation or on any modification to the NPP and its controls.

SELECTION OF NPP SIZE AND TYPE

As in the case of planning for increased generating capacity with conventional units, the optimum economic choice of NPP size may be determined by cost considerations, provided that the unit satisfies the projected grid load demand with specified reserve margins during the plan period. The economics of scale would always favour the selection of the largest permissible unit size of NPP during the plan optimization. The grid reinforcement needed to maintain the desired quality and security of performance from the large NPP unit, as revealed by dynamic simulation studies, should be given due consideration while making the economic choice. Though the best economic performance of an NPP is achieved while operating permanently in base load mode owing to its low fuelling cost, the composition and load pattern of generation in the grid might require a certain amount of load following and/or participation in frequency control by the NPP.

Apart from a clear understanding of the role of an NPP in the normal operation of a power system (base loading being the most common), a satisfactory estimate of the frequency and magnitude of major grid disturbances (faults, loss of line or of generating unit) affecting the NPP is very important in making the right choice of NPP. Most of the disturbances emanating from load–generation imbalance can be handled by proper utilization of the spinning reserve and by load shedding, when necessary. In spite of limited grid reinforcement at the time of the addition of an NPP, the isolation of the NPP into a small island as a result of tie lines tripping on overloading, or planned islanding to save the NPP from a neighbouring grid section where fast restoration of balance is improbable, have a significant probability of occurring. It is during such islanding and house loading operations, and in providing large load following for maintaining the frequency and the voltage of the island, that the satisfactory operation of the NPP without tripping becomes one of the most stringent requirements.

Apart from other factors, the choice of the type of NPP from the point of view of grid suitability would depend on:

- the ranges of voltage and frequency over which the NPP can be operated at nominal power;
- its immunity to random frequency fluctuations occurring in the grid while the NPP is not obliged to maintain frequency control;
- its ability to withstand large load fluctuations in an islanded mode of operation;
- its ability to survive full load rejection and successfully revert to and sustain house load operation until the grid conditions become suitable for resynchronization.

If the cost of the grid reinforcement necessary or the expected rate of grid-induced forced outage is high for the NPP size chosen, it might become more economical overall to have several units of smaller NPPs.

IMPROVING THE GRID–NPP INTERFACE

It cannot be taken for granted that the standardized NPP units, although proven in operation in well developed grids, would operate as successfully in weak grids. Some measures for improving the characteristics of the grid as well as of the NPP are needed. It is better to investigate these measures during planning for the NPP, since most of them can be effectively and economically incorporated before commissioning the NPP, thus avoiding costly retrofitting.

MEASURES FOR GRID IMPROVEMENT

(a) Weak grids operating with insufficient spinning reserves (owing to inadequate growth in generating capacity, a higher forced outage rate than envisaged in the planning, etc.) can lead to large frequency swings following a substantial loss of generating capacity or loss of a tie line, unless effective schemes for automatic control of generation and for appropriate load shedding are implemented. Studies of frequency stability would help determine the appropriate distribution of spinning reserve between various units and the settings for relays for underfrequency load shedding.

(b) The tie line capacity may need to be enhanced to permit the secure transmission of power under all possible load flow conditions. The automatic controls of the tie line should be arranged to isolate safely the grid containing the NPP upon sensing crisis conditions in the neighbouring grid.

(c) Well planned arrangements should be made for stable control of the frequency and voltage, within the operating range of the NPP, in the islands to be formed with the NPP during crisis conditions elsewhere in the grid. It may become necessary to set up additional area dispatch control for islands formed frequently.

(d) Management of reactive power in the grid should be re-evaluated, particularly with respect to the voltage conditions at the terminals of the proposed NPP, which may be located far away from the load centre because of radiation hazard. It may become necessary to add controlled VAR compensators and to regulate generator excitation better.

(e) Any deficiency in existing protection equipment should be rectified to ensure that all faults are cleared within 150 ms. System-wide co-ordination of protective relaying schemes is essential for selective isolation of faulty sections to minimize the disturbances transmitted to the NPP.

(f) High reliability of off-site power to the NPP auxiliaries must be assured by a sufficient redundancy of lines from several nodes of the power grid. Dedicated lines from hydro or gas turbine stations would provide quick startup power for the NPP during grid failure conditions.

(g) Maximum possible attention during planning for operation management should be given to efficient communication between generating stations and load dispatch centres, clearly defined strategies for operating the system during normal as well as contingency conditions and appreciation by system operators of the importance of off-site power to the NPP and clear procedures to ensure its availability.

MEASURES FOR IMPROVING NPP CHARACTERISTICS

It is preferable to introduce all the measures necessary to improve the performance of the grid and to make it suitable for the operation of standard NPP units strictly within its design limits; however, the existing infrastructure and the cost involved may not permit this. The deficiencies remaining in the grid characteristics should be fully recognized while assessing the performance of the NPP chosen, and suitable modifications to the NPP and its controls may be arrived at in consultation with its vendor. The following considerations may often demand design modification.

(a) The capacity of the generator to withstand the extremes of reactive power demanded at nominal power operation.

(b) The capacity of NPP auxiliaries to withstand prevalent fluctuations in voltage and frequency. Slow voltage variations may be taken care of by providing on-load tap changers on station transformers.

(c) The capacity to withstand underfrequency operation during certain peak load conditions without any adverse effect on the components.

(d) The load change and power run-back capability of the reactor, as well as an adequate response speed in the control system for the turbine bypass, which regulates frequency in the islanded mode of operation where the NPP is the major source of power in the island.

(e) The capacity to withstand the expected frequency of grid-induced unit outages and major operations such as house loading with the minimum detriments to components. The need may be felt for additional surveillance instrumentation and increased maintenance efforts.

(f) The extra reliability requirement of an on-site power supply system to compensate for the poor reliability of off-site power. Greater redundancy of diesel generator sets and more frequent testing backed up by better maintenance may be called for.

Most of the above requirements should be possible with only minor modifications to standardized NPPs and their control systems. Major changes in equipment might prove expensive and the advantages of a proven design might be lost. Again, the capacity of the NPP to withstand major disturbances such as full load rejection, turbine trip, step and ramp load change and power run-back under the grid environment should be demonstrated by special tests during commissioning of the NPP.

Modifications that can be postponed until some operational experience of the NPP in the grid has been acquired would include the following: alterations in settings for automatic islanding on low frequency, house loading of the NPP, load limiter and governor settings and undervoltage trip settings for NPP auxiliaries, and improvements in on-site power supply systems such as capacity addition, addition of monitoring and recording equipment and alteration of some control and protective functions without degrading NPP safety. Operating limits on equipment, operational procedures and test and maintenance procedures may all undergo changes with accumulation of experience. Since grid characteristics undergo a steady change over the life of an NPP, whose characteristics remain fairly fixed, a certain amount of retrofitting would be unavoidable.

Planning the operation of the power system to maximize the availability of the NPP and to assure safety through a reliable off-site power supply has to be given due consideration when finalizing plans to increase generating capacity. The planning of the two is so interconnected that the selection of optimum sizes of generating units to meet grid load demand and the simulation studies to ensure dynamic compatibility between the NPP and the grid may have to be repeated iteratively to converge on an acceptable choice of NPP. The relative economics of nuclear power generation in a developing country must be viewed together with the costs involved in the grid reinforcement necessary to ensure a satisfactory level of performance of the NPP or the cost associated with the poor capacity factor the NPP may have in the absence of such measures.

1. INTRODUCTION

Energy, especially electrical energy, is generally taken to be the key to industrial and economic progress. The industrially developing countries, which are late starters in the process of industrialization, are looking for rapid growth in electrical power generation. Almost all the industrially developed countries have embarked on major programmes for nuclear power. The contribution from nuclear power in the power systems of the industrially advanced countries varies from country to country, but in some countries it is a major supplier of commercially produced electricity [1]. The economics of nuclear power depends on many factors; however, in some countries nuclear power has proved to be cheaper, for stations of standardized base load, than power from coal-fired or oil-fired stations [2]. These facts give industrially developing countries a fairly strong incentive to choose the nuclear option, either by outright purchase or by part manufacture, part import under a collaboration agreement. It is in this context that the industrially developing countries should look closely at their own existing power systems as well as at the design and operating characteristics of NPPs for ensuring their safe and economic operation in their power systems.

The power systems in the industrially developed countries today are highly stable and reliable. These characteristics have been attained through technological development spanning many decades and requiring large capital outlays. In addition to the capital expenditure required to build generating capacity sufficient to meet the projected demand, much of this outlay has been utilized to construct reserve capacity, transmission networks and interconnections, protective systems, control systems, instrumentation and communication systems, and in developing highly trained workforces and organizations to execute the various tasks necessary to maintain a highly stable and reliable power system.

NPPs have been designed and manufactured by the industrially developed countries for operation in their existing power systems, albeit allowing for certain tolerances in grid characteristics. NPPs of large unit size have been so successfully integrated into the grids that the economic incentive to opt for large standardized unit sizes is appreciable. NPPs of standardized unit sizes are available from vendor countries in the range of 440 MW(e) to 13 000 MW(e) in capacity. Many developing countries find it difficult to accommodate such units in their small grids [3].

Furthermore, NPPs, as designed today, require a highly stable and reliable grid supply for their auxiliaries. It is likely to be difficult for industrially developing countries to provide the necessary capital, as well as to develop in a short time the technical infrastructure necessary, including management techniques and qualified manpower, to achieve the quality of grid supply achieved by the industrially developed countries over many decades. It is expected, therefore, that grid characteristics in industrially developing countries may for quite some time lag behind those in the industrially developed countries that have successfully integrated NPPs of large unit sizes into their power systems.

While there is a very strong incentive for industrially developing countries to opt for nuclear power, the demand placed on their grids by the NPPs may not be fully met. Operating experience with NPPs in grids of limited capacity has also shown that the safe and efficient utilization of NPPs has been hindered by disturbances originating in the grid as well as by incompatibility between certain characteristics of the grid and those of the NPP. It is necessary, therefore, to understand the interaction of grid characteristics with the design and performance characteristics of nuclear power plants. The Technical Reports Series guidebook TRS-224 [3] published by the IAEA dealt with this matter and has created and awareness of the problem.

The present guidebook is a follow-up to TRS-224 and deals with some of the issues raised in TRS-224 in greater detail and depth. It also provides more specific and prescriptive guidance on the issues, and is intended for utilities, governments and other agencies in the industrially developing countries which are planning to introduce NPPs into their power systems. Its publication is also intended for those who want to achieve greater compatibility between operating NPPs and their grids, as well as for those countries which intend to increase the nuclear component in their grids.

This guidebook will also serve to bring to the notice of the NPP vendors in the industrially developed countries the inadequacies existing and likely to exist for some time in the grids of industrially developing countries. This may help to bring about modifications, where necessary, to the design of NPPs without extra costs to make them suitable for safe and economic operation in grids of limited capacity.

The contents of this guidebook have been organized to give a systematic and detailed treatment of the basic concepts propounded above. Section 2 deals with characteristics of grids and their interactions with the operation of the NPP. It concentrates on the characteristics of high performance grids in which NPPs have been successfully operated. The ways in which deficiencies in these characteristics affect the performance of NPPs have also been illustrated.

In Section 3, characteristics of low performance grids have been described and actual experience of operating NPPs in such grids has been cited. Sections 2 and 3 bring out the difference in conditions prevailing in developed and developing countries, consider the reasons underlying such differences and explore avenues for improvement. These are dealt with in the subsequent sections. Section 4 deals in depth with the design and operating characteristics of various types of NPPs that are standardized and commercially available, and with their compatibility with the characteristics of low performance grids. Section 5 deals in detail with the various steps to be taken for the successful introduction of an NPP into a grid. Section 6 deals with possible measures, such as retrofitting, to improve the performance of NPPs operating in low performance grids. Section 7 describes the various considerations involved and measures to be taken in expanding the nuclear component in a grid. Appendices are provided to supplement the subject matter in the text with specific data and information.

Decisions on whether to introduce NPPs or on what strategies should be followed to achieve better compatibility between operating NPPs and a grid, or on how far to increase the nuclear component in a grid, depend upon many factors which, as well as considerations of the efficiency of operation of the power system, include economic, social and political factors unique to each country. The modus operandi of power system management is to some extent affected by these. It is not the purpose of this guidebook to deal with these factors; nevertheless, such factors cannot be overlooked, and they are touched upon where it is deemed absolutely necessary. This guidebook does not set out to provide definitive solutions to the problems, but is intended to provide an in-depth explanation of the problems and general prescriptive measures for tackling them in a systematic manner.

The topics dealt with are very closely linked; indeed, so closely that it was not possible to organize the text into independent sections without duplication of some vital points.

This guidebook is a follow-up to TRS-224, and although care has been taken to make it self-contained, it is suggested that the reader refer to TRS-224 as and when the need arises.

2. GRID CHARACTERISTICS AND OPERATION OF AN NPP

NPPs of unit sizes of up to 1300 MW(e) have been successfully integrated into the grids of industrially developed countries, whereas NPPs of 220 MW(e) have faced problems operating in the grids of industrially developing countries. A close look at the characteristics of existing grids that have successfully sustained integrated operation is therefore appropriate. Details of the characteristics of such a grid are given in Appendix I. Although the characteristics of high performance grids differ in certain respects, they are fairly well represented in Appendix I. They can be summarized as follows.

- The installed capacity is much larger than (more than ten times) that of the largest unit.
- The grid is quite 'stiff'. 'Stiffness' is defined in terms of the amount of generation loss, in MW(e), required to reduce the system frequency by 1 Hz without load shedding. Loss of the largest unit, in most cases an NPP, does not reduce the frequency by more than 1 Hz.
- The rate of frequency drop caused by loss of the largest unit is quite low.
- The grid has sufficient reserve, including spinning reserve.

- The grid is highly interconnected, with a single interconnection capable of transmitting power exceeding the generating capacity of the largest unit.
- Automatic control of generation is used.
- High speed protective devices capable of clearing any fault within 150 ms are in use.
- A scheme for automatic load shedding based on frequency drop is in use.
- Communication between the generating stations and the load dispatch centre is effective.
- Generation, transmission and distribution of power are well co-ordinated, sometimes by a single agency.
- NPPs are used as base load stations, while the other duties of a power system, such as scheduled load following, frequency control and provision of spinning reserves, are attended to by hydro and thermal stations. In some developed countries NPPs are used to a limited extent in modes other than base load operation.
- The system frequency is controlled more than 99% of the time to within ±0.5% of the nominal frequency and more than 90% of the time to within ±0.1% of the nominal frequency. In effect, the system frequency is kept almost permanently within the dead band (100 mHz) of the governors of stations working as base load stations.
- The system voltage is controlled to within ±5% of the nominal value almost permanently, in fact throughout except during fault conditions.
- In the disturbed condition the system frequency does not fall to such an extent as to cause isolation of an NPP.
- Load shedding incidences are very rare.
- Loss of off-site power has very rarely caused any concern.
- Outage of an NPP caused by grid disturbance is rare.

These are the characteristic features of a high performance grid which make the operation of NPPs of large unit sizes successful. The infrastructure and capital outlay required to acieve such performance and reliability standards in power systems may not be within the reach of industrially developing countries. Such countries may decide to introduce nuclear power and will have to integrate NPPs into grids that are deficient in some or all of these characteristics. It is pertinent, therefore, to examine how these deficiencies are likely to affect the performance of the NPP as well as that of the grid.

2.1. UNIT SIZE IN RELATION TO GRID CAPACITY

An NPP of a large standardized unit size offers an economic advantage when its cost is considered in isolation, without overall consideration of the performance and economics of power system operation. However, if a disproportionately large unit is introduced into the grid, it will cause problems in the operation of the NPP and of the power system as well. This may result in a demand for large investments for reinforcement of the grid in order to maintain efficiency and reliability in the operation of the power system.

When introducing a large unit into a power system, the impact on the grid of forced as well as scheduled outages of such units needs to be examined. NPPs, particularly light water reactors (LWRs), require off-load refuelling (refuelling with the reactor in a shutdown condition) lasting for four to eight weeks every 12 to 18 months of operation, the major maintenance and in-service inspection being undertaken during this period. The scheduled outage of such a large unit requires the provision of a large reserve, either in the form of additional generating capacity or by borrowing through interconnection. In the event that generating capacity is deficient, the power system must undergo sustained underfrequency operation or load shedding, or a combination of both, depending upon the policy adopted by the utility. Moreover, a pressing need for power may put the operation and maintenance staff of the NPP under pressure to bring the plant on line, which in the long term may lead to reduced manpower efficiency and increased manpower costs, as well as ultimately to loss of plant performance.

In cases of forced outage, the restoration of the system frequency will require a large amount of spinning reserve or the borrowing of power through an interconnection. During the initial period of the transient after the NPP has tripped, before the spinning reserves have made a contribution, the downward swing in frequency will be limited by the stored energy, the governor response of other plants, the drop in system load following the drop in frequency, and the power available through interconnection. Much load shedding may be necessary to prevent the frequency dropping to a value low enough to cause stations to isolate or generators to lock out. Furthermore, the overborrowing of power through interconnections may lead to automatic separation of the interconnected systems.

2.2. GRID STIFFNESS

The stiffness of a grid determines the margin available for operating the grid for a limited time at below the nominal frequency without taking recourse to load shedding when part of the total generating capacity in the grid is lost. When a grid is subjected to a disturbance causing the loss of one or more generating units and the utility does not resort to load shedding, the grid frequency drops to a steady lower value. The frequency drop is determined by the load – frequency characteristic of the grid and is solely dependent upon the nature of the frequency dependence of the connected load. For a weak grid with poor interconnections, for which power flow from a neighbouring grid through the interconnection may be of no significance, the grid stiffness will depend entirely upon the load–frequency characteristic of the load connected. This characteristic typically gives a load change of between 1% and 3% for a 1% change in frequency. Outage of a disproportionately large generating unit will force the frequency to drop to a value which may prevent sustained operation of the grid without a large amount of load shedding.

For example, consider a 900 MW(e) NPP operating as a base load station in a power system of 6000 MW(e) installed capacity. With a capacity factor of 0.67:

$$\begin{aligned}\text{Effective generation} &= \text{Installed capacity} \times \text{capacity factor}\\ &= 6000\ \text{MW(e)} \times 0.67\\ &\approx 4000\ \text{MW(e)}\end{aligned}$$

Assuming a load–frequency characteristic of 280 MW(e)/Hz (see Appendix II) for outage of the 900 MW(e) NPP, the grid frequency will drop by:

$$900/280 \approx 3.2\ \text{Hz}$$

if no load shedding occurs.

For a grid operating at 50 Hz, the frequency will drop to 46.8 Hz, which is below the isolation frequency (47 to 47.5 Hz) of most generating units. Tripping of a 900 MW(e) NPP will therefore lead to a grid collapse in this case, if a large fraction of the load is not shed.

2.3. LOAD SHEDDING

When generating capacity is lost, the initial rate of frequency drop is determined mainly by the load–generation mismatch and the system inertia. If the initial rate of frequency drop is high, the system can be maintained in operation only through load shedding.

$$\text{Initial rate of frequency drop } \frac{dF}{dt} = \frac{(L-G)}{G}\,\frac{F}{2H}$$

where L is the connected load (4000 MW(e))
G is the generating capacity (3100 MW(e); a 900 MW(e) NPP is tripped)
F is the frequency (50 Hz)
H is the system inertial constant, usually in the region of 4 MW·s/MVA
t is time.

From the above, dF/dt = 1.8 Hz/s. However, the rate of frequency drop will gradually decrease owing to the governor response and the stored energy in the sys-

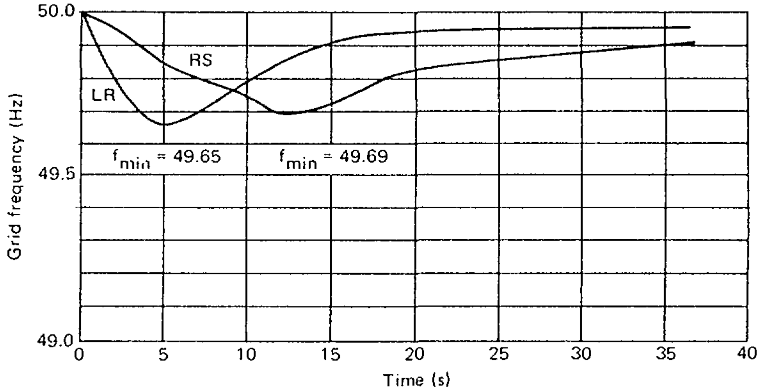

FIG. 1. Transient drop in frequency due to loss of generating capacity in a high performance grid following load rejection and reactor scram. Grid load estimated at 20 000 MW(e). Load rejection (LR), 580 MW(e) (15 July 1975). Reactor Scram (RS), 580 MW(e) (16 July 1975).

tem as well as the load drop due to the reduced frequency. The frequency drop due to the loss of generating capacity in a high performance grid is given in Fig. 1. To safeguard the system, load shedding has to be initiated quite early, and the time delay usually provided with load shedding relays could be quite small in this case. A highly reliable automatic load shedding scheme with a very low probability of spurious operation would be required, since spurious operation might lead to a rapid rise in system frequency.

The situation may be aggravated still further if the incident occurs during an off-peak demand period or precisely during the minimum demand period. Assuming:

$$\text{Demand factor} = \frac{\text{minimum demand}}{\text{maximum demand}} = 0.75$$

We have:

L = 3000 MW(e)
G = 2100 MW(e)
F = 50 Hz
H = 4 MW·s/MVA

$$\frac{dF}{dt} = \frac{(L-G)}{G}\ \frac{F}{2H} = 2.7\ \text{Hz/s}$$

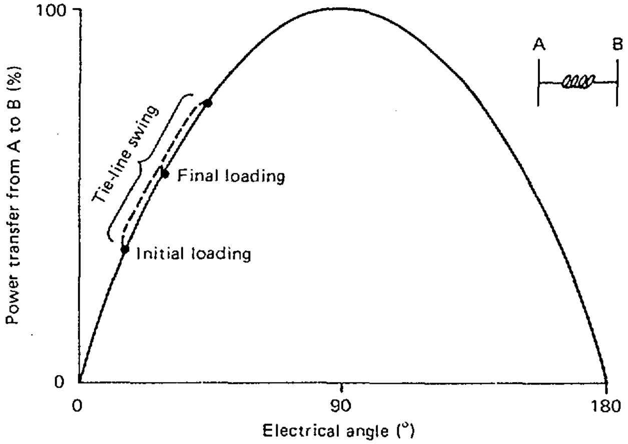

FIG. 2. Simplified representation of the transient power transfer through an interconnection: power transfer (per cent) plotted against electrical angle (degrees).

Although the system has a maximum reserve capacity at minimum demand, the amount that may be available in the first few seconds is limited by the governor response of other plants and the stored energy in the system. In the load shedding scheme, the frequency drop resulting from the amount of load shed, the time delay incorporated in the relays and the total amount of load shed depend upon the down swing in frequency permitted to the power system and the voltage transients which the system can tolerate. However, the load shedding operation, again, is dictated not by technical considerations alone but by socio-economic factors as well.

2.4. INTERCONNECTION

Interconnection helps to achieve a greater stability and reliability of the grid through the exchange of power. This is subject to the proper design of the tie lines and their controls, however. The spinning reserve of the grid can be reduced if the possibility of importing power through the tie line is assured. However, depending upon the location of the NPP, the investment required in the tie lines can be considerable. Loss of the NPP would call for a substantial flow of power through the tie line, and the transient power flow could be twice as large as the generating capacity lost owing to the loss of the NPP (Fig. 2). If tie lines are not of the appropriate capacity and their control system is unable to handle the transient power swing, severance of the interconnection may result, causing major disturbances in both the interconnected regions.

Trips of NPPs are expected to be quite frequent in the initial period of operation owing to teething problems and to the various tests, such as of load rejection and of turbogenerator trip, that are required. The power system may therefore undergo severe disturbances in this period.

In general, it can be stated that a large unit in a comparatively small grid will give rise to the problems mentioned in the foregoing. If the grid is already burdened with such problems, introduction of an NPP of large unit size will severely aggravate matters.

2.5. PROBLEMS IN THE OPERATION OF A POWER SYSTEM

A grid for which the load and the generating capacity are difficult to match needs highly efficient and reliable controls, in particular automatic load shedding and automatic control of generation for manipulation of the spinning reserve (if available); reactive power management and voltage control; instrumentation to monitor the state of the power system; a communication system between generating stations and the load dispatch/energy control centre; and a high speed fault detection and fault clearing capability, owing to the relatively high incidence of disturbances. There are likely to be deficiencies in these areas in grids of limited capacity. Such deficiencies lead to continual small random disturbances and to quite frequent large disturbances. These include those set out in Sections 2.5.1. to 2.5.3.

2.5.1. Frequency and voltage fluctuations

Frequency fluctuations set up transients in the NPP. Normally, NPPs are operated as base load stations. If the frequency fluctuations extend beyond the normal dead band (100 mHz) of the governors, a disturbance is created in the NPP. This is initiated by movement of the governor, causing a change in the steam flow into the turbine. The extent of the effect depends upon the magnitude of the disturbance and the control system response. Different types of reactors — PWRs, BWRs and PHWRs — respond to such disturbances in different manners depending upon their dynamic characteristics and on the behaviour of the control system. The frequency also affects the flow of primary coolant by altering the pump speed and sets up disturbances which are also determined by the dynamic characteristics of the NPP. In a grid with a limited capacity for control, such disturbances are likely to be frequent, and in the long run may lead to a reduction in the life of components, and may necessitate increased surveillance, more maintenance and a higher man-rem budget.

NPP manufacturers recommend a frequency range for normal operation and limits to the period of operation beyond this range. Power output is also limited during operation at conditions of off-normal frequency (see Appendices III, IV and V).

These limitations arise from restrictions on the operation of turbines and the performance of auxiliaries. Sustained off-normal frequency operation due to inadequacy of the power system controls may reduce the life of the plant and leads to increased downtime for additional inspections and maintenance.

Abnormal frequency variations above a certain magnitude will lead to isolation of the NPP, subjecting it to a net load rejection which may lead to its tripping and a total loss of Class IV supply.

NPP manufacturers also recommend a normal voltage range of operation. Operation outside this range is limited in time, the restriction being imposed by the generator and the large motors (the pumps for primary heat transport and for boiler feed). While overvoltage may lead to damage to equipment, undervoltage may lead to tripping of auxiliaries, causing tripping of the NPP.

Unfavourable voltage conditions at the NPP will affect the startup of large motors and delay startup of the NPP after the trip. In PHWRs, where the time required to start up is critical to avoid xenon poison-out, this time delay may impose a serious penalty.

2.5.2. Reactive power imbalance

Inability to generate the reactive power required may lead some of the generators to operate with leading reactive capacity and this puts a restriction on their power output. This may become a very frequent phenomenon with an NPP generator which is connected to the rest of the system by long lines.

2.5.3. Power system faults

A short circuit or ground fault in the system will lead to a severe voltage drop, mismatch between power generation and load, speeding of the turbogenerators and torsional stressing of the turbine shaft, as well as to stresses in the stator winding. Protective devices must be able to clear the faults very rapidly (within 150 ms). Inadequacy in relay co-ordination and relay operation time or in the speed of operation of the circuit breakers may lead to tripping of the NPP owing to tripping of the auxiliary pump motors, loss of synchronization and excessive stress on the turbine shaft.

2.6. COMMUNICATION

Communication using carrier telephony as well as telemetering of data between the load dispatch/energy control centres and generating stations is absolutely essential for the co-ordinated control of the power system as a whole. Any deficiency in this area will hinder the load dispatcher not only in maintaining optimum economic performance of the power system but also in preventing the system from collapsing during faults or loss of generation. Such disturbances may necessitate islanding the NPP and operating the islanded section so as to maintain suitable voltage conditions at the NPP to enable a quick startup and to ensure the proper dispatch of power from the NPP.

2.7. POWER SYSTEM MANAGEMENT

A well-organized grid requires good understanding and co-ordination between the authorities of the generating station and those of the power system. Management of both functions by a single agency would generally make the functioning of the power system more efficient and smoother. This is particularly true if NPPs of large unit sizes are being operated or are being introduced into the grid. The power system management must give due consideration to the characteristics of NPPs, such as: requirements for scheduled outages; restrictions imposed by safety considerations; the impact of voltage and frequency transients on the NPP; requirement for a grid supply of appropriate quality (voltage and frequency) for startup and smooth running of the NPP; the capacity to withstand disturbances in the islanded condition; the capability of surviving net load rejection and remaining on house load; the capacity to tolerate faults on the transmission lines; and the effect of total loss of Class IV supply. An understanding of NPP characteristics on the part of the power system operators is very necessary to minimize the grid-induced outage of the NPP and total losses of power (in the NPP and the grid).

Similarly, NPP operators must be fully conversant with the operating characteristics of the power system as well as with the operating strategies and practices adopted. Such acquaintance in depth enables NPP operators to plan an operating strategy and other means of ensuring the safe and economic performance of the NPP. This would include strategies to decide on isolation of the station and its operation on house load; on operation under islanded condition; on operation under grid transients and off-normal conditions; and on stretching the plant's operation in order to schedule the outage for refuelling so as to accommodate the requirements of the power system.

3. OPERATING EXPERIENCE WITH NPPs IN GRIDS OF LIMITED CAPACITY

A survey of operating experience with NPPs has brought to light the difficulties involved in operating NPPs of even comparatively small unit sizes in weak grids.

Grid-induced outages have been more frequent; potentially unsafe situations caused by the simultaneous loss of off-site and NPP power have been frequent. However, no accident has yet been reported, nor has any damage solely attributable to grid disturbances occurred to major equipment.

It is appropriate to study the characteristics of such grids of limited capacity and their effects on the performance of the NPPs operating in the grids. Some typical data pertaining to such a grid are given in Appendix II. Considerable variation in these characteristics from grid to grid is to be expected; however, some general patterns emerge from the data reported, as follows.

(a) The grid stiffness is quite low and the frequency drop for the loss of the largest unit exceeds 1 Hz, being close to 1.5 Hz. This is mainly due to poor interconnection or the non-availability of power through interconnection from adjacent grids.

(b) The initial rate of frequency drop is quite high for the loss of the largest unit: around 0.5 Hz/s.

(c) There is almost no spinning reserve at peak load, and the stations are operated with the turbine load limiter set near zero. Gas turbine generating sets are used to meet peak demand in some cases.

(d) The demand factor is around 0.6, so there is considerable scope for flattening the load curve to provide some spinning reserve at peak load. The constraints on such measures arise to a considerable extent from socio-economic factors.

(e) NPPs are in some cases not the largest units connected to the grid; the incorporation of other plants of large unit sizes is likely to affect the stability of the grid still further.

(f) NPPs are used as base load stations, thermal stations contribute to schedule load following and hydro stations perform the duty of frequency control.

(g) Interconnections do exist but their capacities are limited and often less than the capacity of the largest unit in one of the interconnected grids. Interconnections or tie lines trip fairly frequently owing to reverse power protection or to overflow of power. Automatic tie line disconnection is not always available and manual operation must be resorted to. In some cases power from the NPP is shared between two neighbouring grids, and during disturbances in one grid the other grid may be disconnected, leaving the NPP connected to the disrupted grid. This subjects the NPP to major disturbances in the grid and leads to tripping of the NPP and the loss of Class IV supply.

(h) Some of the thermal stations become isolated from the grid at a higher frequency than does the NPP.

(i) Automatic generation control (AGC) has yet to be implemented.

(j) Automatic load shedding in a graduated manner with a frequency drop is practised. However, the amount of load shed automatically is restricted to a small percentage, around 10% to 15%; more load is shed manually by the load dispatcher.

(k) Power line carrier communication (PLCC) between the load dispatch centre and generating stations exists, but there are no modern energy control centres equipped with computer systems and data telemetry.

(l) Islanding schemes with NPPs have yet to be implemented.

(m) Suitable arrangements for grid protection with circuit breakers of an appropriate speed usually exist. However, malfunctions sometimes occur in relay co-ordination.

(n) Frequency variation beyond ±1% occurs quite often and lasts for a considerable period. While an operating frequency above nominal is rare, operation under nominal frequency is quite a usual feature. Overfrequency operation is attributable to lack of AGC, and occasionally to lack of a proper working arrangement between the load dispatcher and the various generating units of different authorities. Underfrequency operation is due solely to lack of generation to match the load; authorities sometimes prefer to operate the power system at under the nominal frequency to satisfy the maximum number of consumers for socio-economic considerations. NPPs connected to such grids are operated with their speed governors rendered insensitive to a wide range of frequency variation.

(o) Voltage variations beyond ±5% of the nominal value are also quite frequent, while overvoltage is not very frequent. Undervoltage, particularly during underfrequency operation, is quite frequent. Off-normal voltage conditions are due to shortages of reactive power and the absence of compensators at appropriate locations. Both high and low voltages have been observed at the terminals of NPPs. In some NPPs, underpower relays have been disconnected and the setting of the undervoltage for the motors of the primary coolant pump has been reduced to cope with underfrequency and undervoltage conditions. In some cases unfavourable grid voltages also prevented the timely startup of an NPP after a trip.

(p) The grid-induced outage rate is rather high.

(q) Class IV failure is quite frequent.

3.1. OPERATIONAL STATISTICS

The rates of grid-induced outages reported for NPPs in high performance grids are quite low. For instance, some data available [4] indicate that the grid-induced outage rate for Magnox reactors in the United Kingdom is 0.06 per reactor year. For NPPs operating in Finland, the outage rate is 0.3 per reactor year (Appendix I). Class IV failure rarely occurs. Data available on operating experience with NPPs in weak grids indicate that grid-induced outages are quite frequent and constitute a large fraction of the total outages of the NPP. These may range from four to six per reactor year. Most of the outages occur when the power generation cannot cope with load fluctuations and the NPP becomes islanded; severe frequency and voltage variations lead to tripping of the NPP as a result.

Class IV failures have been quite frequent, varying from 5 to 19 per year. Several of these incidents occurred when the NPP became islanded and subsequently tripped. Many cases occurred when the NPP was in the shutdown condition. The duration of the failure of Class IV supply has been reported to be between 15 and 60 minutes. Case studies related to operating experience with NPPs in weak grids have been described in Ref. [3].

4. CHARACTERISTICS OF NPPs AND THEIR COMPATIBILITY WITH GRIDS OF LIMITED CAPACITY

Because they are difficult to control, grids of limited capacity are likely to undergo disturbances greater in magnitude and longer in duration than those in high performance grids after the same type of initiating events. Incidents such as islanding, station isolation and grid collapse are also likely to be more frequent. Thus the characteristics of the NPP should be examined with reference to the conditions generally expected in limited capacity or low performance grids. A general overview of NPP characteristics is given in Section 3. Appendices III, IV and V also present relevant data on the characteristics of pressurized water reactors (PWRs), boiling water reactors (BWRs) and pressurized heavy water reactors (PHWRs) of standardized designs. Section 4 deals with the relevant NPP characteristics of NPPs, covering PWRs, BWRs and PHWRs, and the implications for their operation in grids of limited capacity.

4.1. REFUELLING

PWRs and BWRs using enriched uranium and light water as moderator and coolant are designed to be refuelled with the reactor shut down (off-load refuelling). In-service inspection and major maintenance which require reactor shutdown are also carried out during this period. These scheduled outages must be considered in the general planning of the maintenance of all units in the power system, since reserve generating capacity must be brought into service to compensate for the non-availability of generation by the NPP. Conditions in the grid may require postponement of the refuelling, since the loss of the generating capacity of an NPP of large unit size would cause a severe shortage of power in a grid of limited capacity. The operation of a light water reactor (LWR) can be extended somewhat by progressively

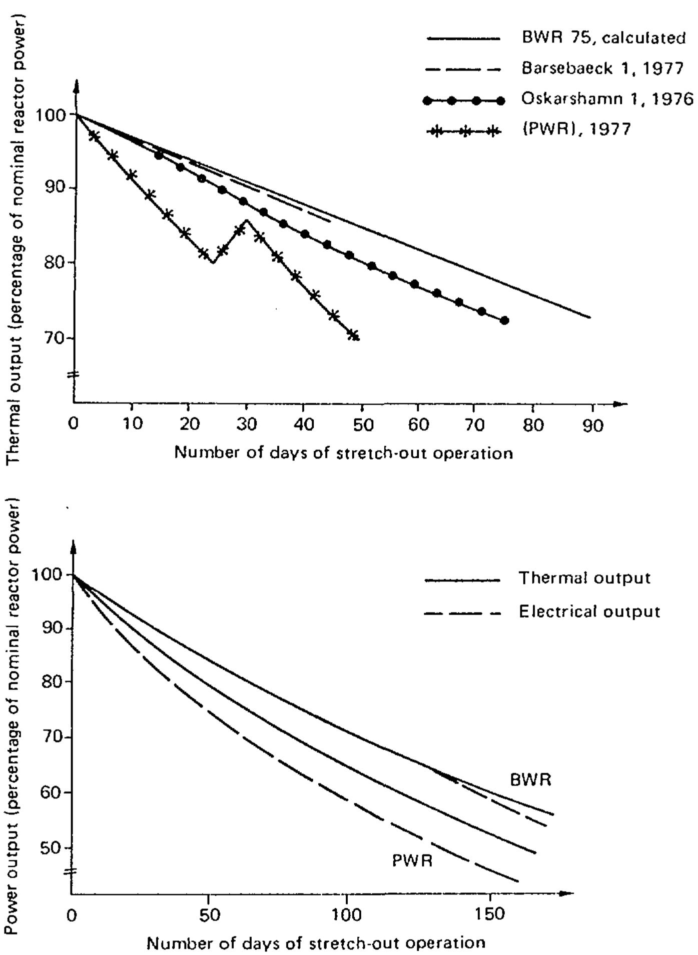

FIG. 3. (a) Thermal output and (b) power output during coastdown operation of LWRs. (Courtesy of ASEA-ATOM, Sweden.)

reducing its power level, the period of extension being termed the coast-down or stretched-out period (Fig. 3). The optimal operating time in the coast-down state is determined by the trade-off between the savings due to the augmented burnup of fuel and the expenditure for replacement power. Flexibility in evolving control rod patterns should be possible, as well as a fuel management scheme to make stretched-out operation viable. Since the reactivity coefficients (the coolant temperature coefficient for PWRs and the void coefficient for BWRs) change and the reactivity available is reduced considerably, the stability of the reactor, the power 'manoeuvrability' of the control system and the time to rise to full power should be examined while planning for such operation. Stretched-out operation adds useful flexibility for NPPs operating in grids of limited capacity. BWRs offer slight economic advantages over PWRs during coast-down operation [5].

PHWRs (using natural uranium as fuel and heavy water as moderator and coolant) operate with on-power refuelling; refuelling is performed daily. This permits greater flexibility in scheduling the shutting down of the NPP for in-service inspection and maintenance.

4.2. TIME TAKEN TO RETURN TO FULL POWER AFTER A FORCED OUTAGE

Since the outage of an NPP of large unit size will cause severe disruption to power grids of limited generating capacity, the length of time taken by NPPs to return to full power after load rejection, tripping or shutdown is important. This time depends on temperature conditions in the plant (the reactor and other parts of the plant, including the turbine); the reactivity reserve available (of particular concern for CANDU PHWR reactors); restrictions imposed by interactions between pellets and cladding on fuel loading (not relevant for the CANDU PHWRs); thermal stress in various reactor components and in the rest of the plant, including the turbine; and the ability of the control systems to keep the parameters of the plant within limits during power ramping. The time required to reach full power from the hot tripped condition is around four to six hours for the NPPs, which includes the time required for heating up steamlines and feedwater and condensate lines.

In PWRs the rise in power is effected through the movement of control rods; care must be taken in controlling the power distribution that the power density nowhere exceeds the permitted limit. The poisoning effect of xenon is taken care of by removing boron from the moderator. Near the end of the fuel cycle the effect of boron dilution becomes progressively reduced, and the rise in power can be effected only at a much slower rate.

In BWRs the rise in power is effected by varying the recirculation flow and the movement of control rods. The time taken to reach full power from a hot tripped condition is around five to six hours (see Appendix IV).

During the first rise to full power or the subsequent increase to full power after refuelling, restrictions are imposed by pellet-cladding interactions (PCI) in the fuel. The fuel has to be soaked at various power levels during the rise to full power, which it may take up to three weeks to reach. Such restrictions are applicable to LWRs only and not to the CANDU PHWR, where a different design (collapsible cladding) for the fuel is used.

Starting up the reactor from cold conditions requires much more time owing to the time required to warmup all the systems. A warmup rate of 30–40°C per hour can be expected for LWRs. However, various tests are usually associated with a cold startup and the minimum time required for starting up large LWRs from cold may be around 20 hours.

A CANDU PHWR, when tripped from steady state operation at full nominal power, has to be brought back to at least 65% of nominal power fairly quickly (typically within 30 minutes) to prevent poison-out of the reactor. Power recovery from a short outage after tripping (less than 30 minutes) to around 70% of nominal power can be very fast (at a rate of 12% to 60% per minute). The time taken to restore full power is considerably longer, from four to six hours, because of the time required to overcome xenon transients through movement of the adjuster (control) rods.

Full power can be restored within 4.5 hours after a poison outage of about 36 hours if the primary heat transport (PHT) system is maintained in hot condition. This includes the time required for drawing the condenser vacuum, heating up the steam piping and loading the turbine. No restriction is imposed by the effects of xenon and of the flux distribution.

The warmup rate for the PHT system in CANDU PHWRs is 5°F per hour. A minimum of six hours is required for CANDU PHWRs to reach full nominal power from cold conditions (see Appendix V).

4.3. THE DYNAMIC CHARACTERISTICS OF NPPs

The dynamic characteristics of an NPP are defined by its responses to various disturbances, including those originating in the grid. These characteristics, together with operational requirements, determine a suitable design of control system. The capability of the system to withstand large transients without tripping is also determined by the dynamic characteristics of the NPP.

The parameters affecting the dynamic characteristics include the energy and mass storage in various components such as the reactor pressure vessels and the steam generators; the inertia of pumps and of the turbogenerator; heat transfer coefficients; the pressure differences in piping and valves; and, typically for nuclear reactors, reactivity feedback coefficients. Reactivity feedback coefficients give the NPP a dynamic response substantially different from that of fossil fuelled thermal stations. Reactivity feedback arises from a change of temperature of the fuel and a change of temperature of the moderator or a void fraction in the moderator. In a PWR the coolant acts as a moderator, and therefore a change in the temperature of the coolant gives rise to reactivity feedback. In a BWR, boiling coolant serves as the moderator. In a CANDU PHWR (a PHWR with a pressure tube design) the moderator is separate from the coolant and is kept at a constant temperature.

In a PWR the moderator/coolant temperature coefficient of reactivity is negative, meaning that when the temperature of the coolant increases it introduces a negative reactivity into the system which reduces the reactor power. Being of indirect cycle design, this imparts a self-regulating characteristic to a PWR. In a BWR the moderator/coolant void coefficient of reactivity is negative, implying that when the void fraction in the moderator/coolant increases, a negative reactivity is introduced into the system which reduces the reactor power. This effect introduces an instability into the dynamic response of the BWR, since unlike the PWR it is of a direct cycle design. In the CANDU PHWR the temperature coefficient of reactivity of the coolant is negligible, and as such the temperature variation of the coolant has no effect on the dynamic characteristic, except by causing a pressure change in the system.

4.4. THE DYNAMIC RESPONSE OF THE NPP TO A CHANGE IN THE GRID FREQUENCY

The dynamic characteristics of the NPP stated earlier indicate the effect of a change in the temperature of the primary coolant or in the primary coolant void. These are affected by a frequency change by way of a governor response or change in primary coolant flow. In a high performance grid the grid frequency is controlled within the usual dead band (100 mHz) of the turbine governors of the NPP. Except in cases involving the loss of a large amount of generating capacity or load, leading to a considerable variation in frequency, the governors of NPPs operating as base load stations will rarely be subjected to any movement. The variations in frequency in a grid of limited capacity are beyond the dead band for a large fraction of the operating time, and large variations in the steam flow through the turbine will occur, causing transients in the NPP, if the governors are kept free to respond to the change in frequency. If the drop in the governor is 5%, a 1% frequency change (0.5 Hz in a 50 Hz system) will cause a 20% change in power output from the turbine. A change in the position of the governor valve causing a change in the steam flow to the turbine causes a change in the pressure in the steam generator and in the reactor. This leads to a change in the temperature of the primary coolant, in the void fraction and in the primary coolant pressure, and introduces reactivity feedback which alters the reactor power.

For a PWR, an increase in the grid frequency leads to a rise in the temperature of the primary coolant and introduces negative reactivity feedback which reduces the reactor power automatically without any control action. Similarly, the reactor power rises when the frequency falls. Thus PWRs become inherently self-regulating, which greatly helps control systems to bring about load following.

In a direct cycle BWR, an increase in grid frequency causes the reactor pressure to rise owing to a reduction in the flow of steam through the turbine. An increase in the reactor pressure will lead to reduction in the void, which will introduce positive reactivity in the system and increase the reactor power. Conversely, a decrease in frequency leads through governor action to a reduction in reactor power. This gives rise to an inherent instability in the dynamic behaviour of BWRs subjected to a load disturbance, and suitable control action must be taken to avoid such instability.

In a CANDU PHWR, an increase in frequency leads through governor action to a rise in the pressure in the steam generator and rises in the average temperature of the primary coolant and in the primary pressure. However, since the temperature coefficient of reactivity of the coolant is negligible, no feedback reactivity is introduced into the system and no change in reactor power occurs. If the grid frequency falls, increased steam flow through the turbine causes a drop in the pressure in the steam generator, a reduction in the average temperature of the primary coolant and in the primary pressure.

If the governor is allowed to respond to the frequency variations that normally occur in weak grids and lead to variations in the flow of steam through the turbine, transients are set up in the NPP. These cause the pressure in the steam generator to vary in the case of the PWR and the CANDU PHWR and cause the pressure of the primary coolant to vary for PWRs, BWRs and CANDU PHWRs. The reactor power varies for PWRs and BWRs, although its upper bound will be limited by the turbine load limiter and systems for limiting the neutron flux. These dynamic characteristics form the basis of control system design, determining the ability to withstand major disturbances such as load rejection and turbine trip, and the flexibility of operation in different modes such as on base load, under scheduled load following and under grid frequency control.

The frequency variation also affects the flow of primary coolant in PWRs and in the CANDU PHWR by causing a change in the pump speed. Since primary coolant pumps in both CANDU PHWRs and PWRs are provided with large inertia flywheels, the flow of primary coolant will not be affected by a frequency change of short duration (around two to three seconds). The change in the flow of primary coolant is proportional to the change in frequency. For a PWR or a CANDU PHWR this flow change causes a slight change in the average temperature and pressure. In a BWR, where the recirculation pumps are operated through motor generator sets or thyristor controlled frequency converters, frequency variation would not normally affect the recirculation flow and would not cause any transient.

Changes in frequency also affect the power drawn by the auxiliaries, which varies approximately as the cube of the frequency. The operating point of the pumps and other centrifugal equipment also shifts, causing changes in coolant flows, the effects of which have already been discussed.

4.5. THE DYNAMIC RESPONSE OF AN NPP TO A CHANGE IN GRID VOLTAGE

A change in grid voltage generally affects the performance of electrical equipment such as generators, transformers and motors but does not set up transients in the process systems of the NPP. In the case of a large voltage drop and subsequent recovery, as happens in the event of a fault and its subsequent clearing, the pumps in PWRs and PHWRs, having been provided with large inertial flywheels, do not decelerate and subsequently accelerate. However, the recirculation pumps, in BWRs which have thyristor-controlled frequency converters, will decelerate initially, causing a reduction in the recirculation flow and a reduction in reactor power. When the fault subsequently clears and the voltage rises, the motors will accelerate, causing an inrush in currents, an increase in recirculation flow and an increase in reactor power. The magnitude of the disturbance will depend upon the magnitude and duration of the voltage dip.

4.6. THE ABILITY OF THE NPP TO WITHSTAND LARGE TRANSIENTS

Incidents such as net load rejection, i.e. disconnection from the grid, and gross load rejection, i.e. opening of the generator breaker and turbine tripping, which cause severe transients in the process systems of the NPP, are anticipated occurrences which the NPP should be able to withstand without tripping. In the case of turbine tripping or generator tripping the onus of maintaining a stable grid supply to avert the total loss of Class IV supply is on the authorities for the grid. However, the onus lies on the NPP in the case of net load rejection. It is imperative, therefore, that net load rejection while the NPP is at full power does not lead to tripping of the turbine or the reactor. This is all the more important for NPPs operating in grids of limited capacity, since such occurrences may be rather frequent. Load rejection events may arise through the deliberate action of operators of NPPs who isolate the NPP from the grid to prevent its operation under unfavourable grid conditions.

In load rejection, there is severe mismatch between the mechanical energy input to the turbogenerator and the electrical load, causing the turbogenerator to speed up. This excess input energy to the turbine is cut off by closure of throttle valves and interceptor valves by speed-sensitive action of the governor. The rate of speed increase (acceleration) depends upon the inertia of the turbogenerator and the response and speed of closure of the throttle and interceptor valves. The speed of closure of the interceptor valves is also important where reheaters with a large capacity for steam are used. The stored steam may lead to overspeeding of the turbine if the interceptor valves do not close quickly enough.

On a net load rejection in an NPP at full power, the turbine overspeeds by 6% to 8%. The overspeed may last for about one minute before it is brought down to normal values. The auxiliaries must perform satisfactorily during this disturbance. The turbine is protected by quick-acting stop valves which usually activate at 9% – 10% overspeed. Tripping of the turbine after separation of the NPP from the grid will lead to a complete loss of Class IV supply. The speed control devices such as the speed governor, the throttle valve and the interceptor valves should ensure that the turbine speed does not reach the overspeed trip value after the NPP operating at full power separates from the grid. The quick cut-off of steam by the speed governor in the event of load rejection or by the emergency stop valve in the event of turbine tripping rapidly closes the sink for the energy generated by the reactor. The excess generated energy is absorbed by the reactor fuel, the primary coolant and the secondary coolant, raising their temperatures and pressures.

In a PHWR this leads to sharp increases in the steam pressure in the steam generator, in the temperature and pressure of the primary coolant and in the fuel temperature; however, the reactor power is not affected.

In a PWR, the steam pressure in the steam generator, the temperature and pressure of the primary coolant and the fuel temperature are affected in a similar fashion. However, an increase in the reactor coolant temperature introduces negative reactivity feedback and reduces the reactor power. However, the effect of this power reduction is felt in the rest of the system with a time delay of 8 – 10 seconds (the fuel time constant).

In a BWR, load rejection or a turbine trip is followed by a rapid rise in pressure in the reactor vessel. This rapid rise in pressure causes the voids to collapse. The void collapse introduces positive reactivity into the system and causes the neutron flux to rise sharply.

Occurrences such as load rejection and turbine tripping introduce large and fast transients in the NPP and cause wide deviations of the main process parameters at a rapid rate. Control systems of NPPs do not have sufficient speed of response to handle such transients. Quick-acting devices are therefore necessary to ride over these transients without tripping or actuating the relief devices of the NPP. This is achieved by dumping the steam into the condenser and/or the atmosphere through fast-acting dump valves or bypass valves. These valves are actuated by a signal of the pressure in the steam generator in the case of PWRs and CANDU PHWRs and by a signal of the reactor pressure in the case of BWRs, and they are meant to match the energy input by dumping steam. The capacity and speed of opening of the bypass valve are chosen so that the process parameters such as the primary coolant pressure are kept within trip limits; so that overdumping, which might lead to these parameters dropping below an acceptable value, does not occur; and so that the condenser vacuum is not broken.

PWRs usually provide a less than 100% dumping capacity for the steam flow. Some PWRs of larger unit sizes cannot survive a reactor trip if a turbine trip occurs while the NPP is operating at more than 50% of its nominal power. CANDU PHWRs and BWRs have a steam flow bypass capacity rated at slightly more than 100%. The bypass control system requirement is the most stringent for BWRs because of a sharp rise in the neutron flux. The fastest operating bypass valves are provided on BWRs; the speed of opening can be as fast as 300% per second. In PWRs and CANDU PHWRs, bypass valves with a total opening time of around 2 seconds are provided. However, as stated earlier, the size and response of the valves depend upon the dynamic characteristics of the NPP and may vary. The choice of the condenser dimensions to deal with steam dumping during a transient without breaking the vacuum is also an important factor in providing a steam bypass capacity.

During these occurrences it is judicious to reduce the reactor power, the rate of reduction being determined by the requirements imposed by the disturbance and by the capability of the control system. For a PWR such disturbances, which lead to an increase in the average temperature of the primary coolant, automatically induce the control system, which acts on the basis of maintaining a constant average temperature of the primary coolant, to move the control rods in and reduce the reactor power. In the process it is aided by the inherent self-regulating character of the PWR conferred by the negative temperature coefficient of reactivity of the coolant. If a faster reduction is desired, a partial scram of the reactor is initiated.

In a BWR the reactor power is quickly brought down by rapidly decreasing the recirculation flow wherever possible, depending upon the time constant of the recirculation flow system. In BWRs that use solid-state-controlled frequency converters for varying the speed of the motor, such a practice is adopted to bring down reactor power in case of load rejection or turbine trip [5]; in case a quick reduction in the flow is not possible, for occurrences of load rejection in excess of 50%, half of the recirculation pumps are tripped to bring down the neutron flux and the reactor power rapidly. In either case a further reduction of power is achieved by the fast insertion of control rods (a partial scram).

CANDU PHWRs, when provided with adequate (more than 100%) steam bypass capacity, do not require a reduction in power by the control system for surviving load rejection without tripping. However, a facility for automatic power runback through the control system is provided.

The capability of the NPP to survive large disturbances such as load rejection and turbine tripping essentially depends on the capability of the bypass control system, including the satisfactory operation of the bypass valves. A reduction in power by initiating rundown has its effect subsequently, since its action is delayed by the control system response and by the fuel time constant. A high degree of reliability is required of the bypass control system and the valves, since their malfunction, including becoming stuck open, would result in outage of the NPP as well.

If the disconnection from the grid is expected to last a short time (a few minutes), it may be desirable not to reduce the power of the NPP and to increase its power again after resynchronization, but to continue operating the reactor at near full power while catering for its own load, i.e. the load of the auxiliaries and of bypassing the excess steam. It is possible to operate the NPP in this condition. The penalty is economic; i.e. the unnecessary burning of fuel, and the investment required in providing a suitable condenser capable of handling the continuous steam dump without breaking the vacuum. CANDU PHWRs operating with natural uranium as fuel suffer the least economic penalty. However, if bypassing involves discharging steam into the atmosphere as well as the condenser, the reactor power should be reduced to a level where the valves discharging steam into the atmosphere remain closed, thus preventing the unnecessary loss of demineralized water. For a CANDU PHWR operating at less than 70% of full power, therefore, the bypass control systems should be so designed that load rejection or turbine tripping does not require the opening of these steam discharge valves, and the process parameters of the NPP can be controlled within limits by dumping steam in the condenser only.

The auxiliaries in NPPs are usually supplied through two paths. These are:

(a) through the NPP generator and the unit auxiliary transformer;
(b) through the grid and the startup transformer.

Two paths are chosen so that all the auxiliaries can be supplied from one source if required through auto/manual transfer. Usually the main auxiliaries such as the main circulation pumps are divided equally between the generator and the grid. In the event of the loss of one source, the loss of grid supply in the case of severance from the grid, or the loss of supply from the NPP due to generator or turbine tripping, auxiliaries are automatically transferred from the lost source to the available source. In the event of absence or malfunction of the autotransfer, half of the auxiliaries, such as the main circulation pumps, will be lost. This will lead to a flow coast-down.

In PWRs and PHWRs the flow coast-down will raise the temperature and pressure of the primary coolant and the temperature of the fuel. In order to control these parameters within operating limits, a rapid reduction in power is necessary. In a PWR this can be achieved by a partial scram, as well as being aided by its self-regulating characteristic. In a PHWR the power reduction is achieved through a set-back/step-back mechanism. If the characteristics of power reduction and flow coast-down are not properly matched, load rejection coupled with loss of half the main circulating pumps may lead to tripping of the NPP, resulting in a total loss of Class IV power.

In a BWR, however, loss of half the recirculation pumps reduces the reactor power by almost or by more than 50%. However, since the flow coast-down is also much more rapid than for PWRs and PHWRs since internal recirculation pumps in BWRs are not provided with flywheels, a still further reduction in power by a partial scram may be necessary to prevent drying out of the fuel cladding. However, this depends upon the dynamic interaction between the decaying power and the flow during coast-down.

4.7. POWER RUN-BACK

NPPs are provided with a facility to run down the reactor power manually and/or automatically. The necessity to run down the reactor power may arise as a result of conditions occurring either in the NPP or external to the NPP (originating in the grid). This facility is the first line of defence, limiting the deviation of process parameters below the trip values when the disturbances in the NPP cannot be adequately handled by the control systems. These disturbances may arise as a result of the loss of one or more circulating pumps, loss of the feed pump, malfunction of the control system, or component failure. The power level to which the reactor is run back is determined by the values of the process parameters. When the run-back or set-back is automatically initiated by the process parameters, it stops automatically when the values of process parameters such as the primary coolant pressure, the boiler pressure and the boiler level are within acceptable ranges. In the case of manual initiation and/or termination of set-back by the operator, close monitoring of process parameters is necessary.

In the case of power run-back, particularly for reasons internal to the NPP, care should be taken that the energy input to the turbine is properly controlled so as not to create a serious mismatch with the reactor power. Such a mismatch can lead to deviation of the process parameters and tripping of the NPP. The turbine loading set point as well as the load limiter set point should be automatically lowered, together with the power run-back of the NPP. The load dispatcher should obtain information on the run-back of the NPP immediately so that the reserves can be arranged to compensate for the loss of generation, or recourse can be taken to load shedding. In a grid of limited capacity, run-back of an NPP of large unit size can create considerable disturbances in the form of underfrequency. It is essential that the turbine load limiter functions properly during the run-back, since the underfrequency created in a small grid by the loss of NPP generation might otherwise cause a turbine throttle to open relatively wide, leading to an excess of power withdrawn over power generated and subsequently to tripping of the NPP, mainly because of low primary coolant pressure.

Power run-back may also be initiated for reasons originating in the grid. During unfavourable conditions in the grid, the NPP can be islanded with a reduced load or may even be totally severed from external connection, needing only to supply its own house load. Whereas for an NPP in an islanded condition the extent of the power run-back depends upon the load on the islanded section and the generation from other stations in the island, the extent of the power run-back on house loading is dependent upon the lowest permissible operating level for the NPP, since the house load requirement is only 5 – 10% of nominal power.

In PWRs run-back can be initiated by running down the turbine load set point, which will automatically cause control rods to be inserted into the reactor to reduce the reactor power. This method is adopted since PWRs in the power range are controlled on the basis of 'reactor-follow-turbine' philosophy which exploits their inherent self-regulating feature. Otherwise, a quick reduction in power can also be achieved by a partial scram. The reduction in power is effected entirely by way of the control rods alone.

In BWRs, power run-back is effected by reducing the speed of the circulating pumps to reduce the circulation flow. Control systems for the pump speed using thyristor controlled frequency converters have small time constants and can alter the circulation flow rapidly. Power run-back up to the 60% level can be effected at the rate of 20% per minute using these control systems [5]. In BWRs in which control valves are used for recirculation flow control, an equally rapid rate of power reduction is possible.

A further reduction in power can be effected by the rapid insertion of a group of control rods (a partial scram). Wherever a rapid reduction in power is not possible, the system power is reduced by tripping half the recirculation pumps, which brings the power down to near the 50% level.

In CANDU PHWRs, when operated in the 'turbine-follow-reactor' mode, the power run-back is effected by running down the reactor power set point; this moves the control rods in by the action of the reactor regulating system. The set-back action is automatic with the provision of manual operation, and a maximum rate of 1% per second is provided. In some designs, where the steam bypass capacity is less than 100%, a step reduction in power by dropping control rods (step-back) is also possible (see Appendix V).

4.8. OPERATION IN ISLANDED AND HOUSE LOADED MODES

When there is a serious disturbance in the grid, it becomes necessary to divide the grid into various parts, and the NPP, together with some generators and connected load, may form an island. If the grid is under automatic generation control (AGC), this mode is discontinued and the islanded section containing the NPP is then subject to local controls. In grids of limited capacity, the NPP may become located owing to islanding in a section where it constitutes a disproportionately large fraction of the total generating capacity connected.

The NPP is therefore subjected to large disturbances, and suitable operating strategies should be adopted for the NPP as well as for the grid to keep the NPP operating. Control of the grid frequency within the specified operating band of the NPP is a major task. For the NPP, the requirements include automatic power run-back, power level control and operation in a steam bypassing mode. Grid operation demands graded load shedding on the basis of the system frequency so that the NPP does not trip or become isolated.

Survival of the NPP, which forms a large fraction of the generation connected in the islanded section, is essential, since tripping of the NPP invariably leads to a grid collapse. If the grid conditions exceed permissible limits, it becomes necessary for the NPP to shed all loads and take on its own house load to prevent tripping. Thus it is important that the house loading operation is successful and does not lead to tripping of the NPP, which would cause a total loss of Class IV supply. However, such operation should be resorted to only under extreme conditions, since its success depends upon the correct functioning of many devices and the margin of inefficient operation permitted for these devices is small. Besides, each load rejection, whether successful or not, impose stresses in the components, the more so if the operation is unsuccessful and leads to tripping of the NPP. After reaching house load, the NPP is required to sustain operation in this mode until the grid conditions improve enough for resynchronization and a rise in power from the NPP. Usually this might take 10–15 minutes, but in grids of limited capacity the period may be up to 1 hour.

There is usually no limitation put on the period of operation by the reactor, although restrictions may arise from the turbine. The restriction in the CANDU PHWR is due to the limitation in its reactivity reserve for overcoming xenon poisoning; consequently the CANDU PHWR must operate at or above the power level at which poisoning is prevented (65%) in the steam bypass mode.

4.9. FREQUENCY AND VOLTAGE LIMITS OF OPERATION

NPP vendors specify the nominal full power range of operation within ±1% of the nominal frequency, i.e. 49.5–50.5 Hz, and restricted operation in power as well as in time beyond this band, for 50 Hz systems[1]. The restrictions arise from considerations concerning the turbines, the generators, the motors for auxiliaries and the primary coolant flow.

Off-normal frequency affects the bucket life of the turbine (Fig. 5, Ref. [3]). The closer the operating frequency is to the critical frequency, the greater is the damage and the reduction in turbine life. Both the frequency and the voltage affect the excitation system of transformers and generators and cause overheating of the generator stator windings and the transformer windings. The stability margin of generator operation is also affected by voltage (Figs 2 and 3, Ref. [3]). The current drawn by large motors is affected, possibly causing overheating and tripping.

The frequency range for restricted operation under off-normal frequency and voltage conditions varies from manufacturer to manufacturer. However, all manufacturers recommend that the NPP should not be operated at below 48 Hz or above 51 Hz, and a linear decrease in power output from the turbine is recommended starting from 49 Hz [1]. The station isolation frequency, at which the NPP is separated from the grid, is kept between 47.5 and 48 Hz, and the underfrequency protection for the generator is kept between 47 and 47.5 Hz, with or without a time delay of a few seconds to a few minutes.

Some typical figures from an NPP vendor regarding the voltage and frequency limits of operation for 50 Hz systems are given in the following.

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[1] Similar percentage margins are provided by vendors for 60 Hz systems.

TABLE I. LIMITING FREQUENCY AND VOLTAGE CONDITIONS FOR THE DISCONNECTION OF AN NPP FROM THE GRID

Frequency (per cent)	Generator terminal voltage (per cent)	Duration	Plant output (per cent)
102 –104	95– 105	5 s	100[a]
100.5–102	95–105	1 h	100
99.5–100.5	90–95	1 h	100[b]
97 –98	95–102	30 min[c]	95[d]
96 –97	95–100	20 min[c]	90[d]
95 –96	95–100	10 min[c]	85[d]

[a] Plant output decreases linearly with increasing frequency in accordance with turbine governor drop.

[b] Maximum 2 h per year.

[c] Only occasional disturbances.

[d] Linear reduction in output with decreasing frequency.

Normal operation is assumed to be between 49 and 50.25 Hz (98—100.5% of nominal) with a generator terminal voltage of 95—105% of nominal. The power output of the turbine decreases linearly with frequency when the plant operates at frequencies below 49 Hz (below 98% of nominal).

Operation at full power in the range 49.75 – 50.25 Hz (99.5 – 100.5% of nominal) is limited to 1 hour at generator terminal voltage between 90% and 95% of nominal.

The minimum operating frequency is 48 Hz (96%) for 10 minutes, after which period the plant is isolated from the grid.

The generator lockout frequency is 47.5 Hz (95%) for 6 s.

The power plant is designed to withstand the frequency and voltage conditions shown in Table I without being disconnected from the grid.

4.10. THE EFFECT OF VARIATIONS IN THE VOLTAGE AND FREQUENCY ON THE PERFORMANCE OF AUXILIARIES

During normal operation in a high quality grid the frequency and voltage are maintained within ±0.5% and ±5% of the nominal value. However, a wider range, from −1 Hz to +0.5 Hz for 50 Hz systems is usually taken as the normal operating range of auxiliaries[2]. In a disturbed condition, both the voltage and the frequency are expected to vary within a much wider range, though for a limited period. In grids of limited capacity, the voltage and frequency might remain outside the normal operating range for considerably longer than would be expected in a high performance grid.

Voltage variations affect the performance of large induction motors. Undervoltage causes overdrawing of current and may cause tripping of the motors by overload, possibly leading to tripping of the reactor. The startup of large motors while there is an undervoltage causes a drop in voltage and may trip the operating motors as well by undervoltage protection. Overvoltage results in an increased excitation current and heating up of the stator windings. The current drawn by the motor varies as the cube of the frequency. An operating voltage of 90% of nominal and a frequency of 51 Hz will cause the current drawn to increase by 18% [5]. The lines, breakers, etc. need to be designed to carry the current for the period for which the off-normal conditions are likely to persist. During load rejection the turbogenerator overspeeds by up to 6−8% of the rated value. This overfrequency condition may last until the speed governor brings down the speed of the turbogenerator to the rated value. The overfrequency may last up to 1 minute, depending upon the steam energy stored in the reheaters and in the low pressure cylinders, the governor response, the speed of operation of the throttle and interceptor valves, and the inertia of the turbogenerator [5].

The motors for auxiliary services such as primary coolant pumps, boiler feed pumps, the station auxiliary transformer, lines, circuit breakers and protective relays should be capable of sustaining operation during this period. This overdrawing of current by the auxiliaries will cause a further voltage drop in the transformers and lines and will reduce the terminal voltage across the motors, since the exciter of the generators is capable of controlling the terminal voltage at the generator within the specified limit (95-105%).

Underfrequency operation will also cause the process flows, such as the primary coolant flow, to change. The flow change is almost directly proportional to the frequency change. Flow reduction may call for an automatic power reduction and flows reduced still further may call for a reactor trip (93−95% for PWRs and for the CANDU PHWR). However, short-term frequency changes lasting for a few seconds, as occur during the initial period of the disturbance caused in the grid by loss of generation, do not affect the speed of primary coolant pumps.

The generator bus bar voltage can be controlled by the excitation control system within 95−105% at all loads. However, the main transformer terminal voltage

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[2] Auxiliaries having similar operating ranges of voltage and frequency for 60 Hz systems are also available from manufacturers.

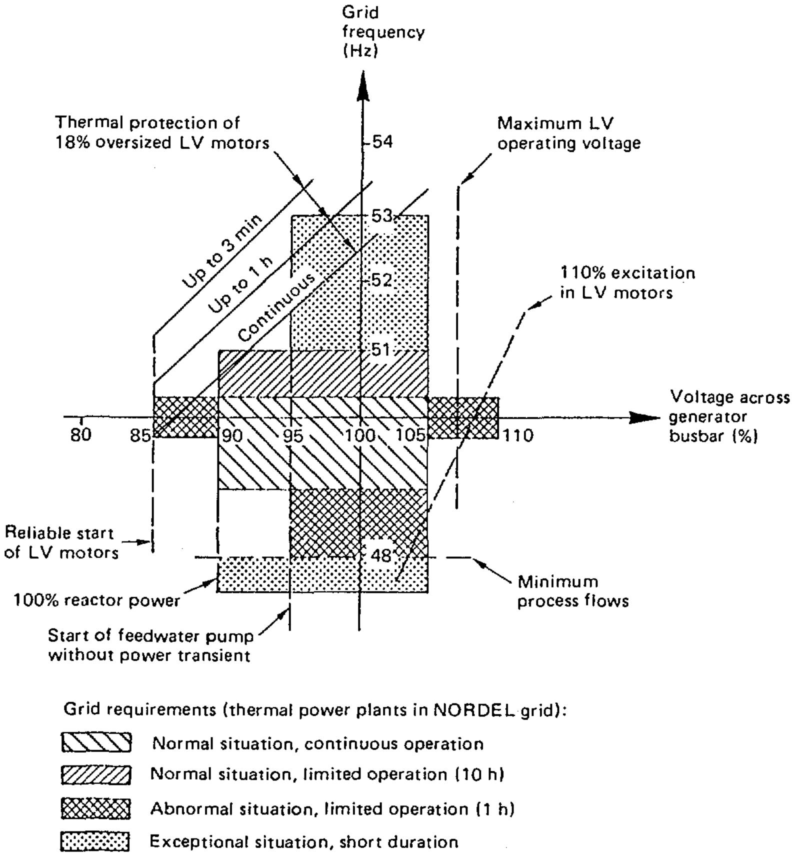

FIG. 4. Plant adaptation to grid requirements: examples of limitations on plant auxiliaries. (Courtesy ASEA-ATOM, Sweden.)

may vary over a wider range depending upon the grid conditions. The station auxiliary transformers fed through the main transformer need to be provided with on-load tap changing gear if the main transformer is not so provided. The station auxiliary transformer fed from the generator should also be provided with on-load tap changing.

Appropriate voltage conditions are required for starting up large motors. Usually these are capable of starting at a voltage level of 80–85% of the nominal voltage. However, the transformer, the lines, the breakers and the protection relay systems should be appropriately designed.

The transformers are usually provided with total 10% tap changing. If the voltage conditions in grids of limited capacity require a larger margin, this has to be considered with regard to all aspects of the electrical system catering to auxiliaries.

On-load tap changing is rather slow (order of one minute) and cannot compensate for rapid voltage changes. However, this voltage disturbance of very short duration is not of major importance to the NPP auxiliaries.

The permissible frequency and voltage band for the satisfactory operation of auxiliaries vary according to the manufacturer. Figure 4 presents some typical examples of limitations on frequency and voltage for plant auxiliaries.

4.11. THE PERFORMANCE OF CONTROL SYSTEMS

The performance of an NPP is determined to a large extent by the capabilities of its control systems. The important parameters such as the neutron flux, the primary coolant pressure, the steam generator pressure, the water level in the steam generator/reactor vessel, the speed and power output of the turbogenerator, the generator voltage, etc., are kept within the operating range during any disturbance originating inside the NPP or outside (in the grid), or during routine power operations such as power runup, scheduled load following operations, or participation in grid frequency control, by the control systems of the NPP. Even during the so-called steady operational state of the power system there are random fluctuations in grid frequency which may disturb the NPP. The power generated from the NPP operating at a constant power level also declines with time owing to the loss of reactivity caused by the burnup of fissile material (fuel) and the buildup of fission products (poisons), which necessitates control action to maintain the power level. For the CANDU PHWR, however, this depletion in reactivity is compensated for by on-power refuelling.

The NPP, being a part of the power system, may be required to operate as a base load station or to participate in a load following operation, or to operate in both modes depending upon the network demand. The choice of operating mode depends upon the existing network, the economic penalty associated with the load following operation, the design and operational characteristics of the NPP and the capabilities of the control systems. At present the generally adopted mode of operation of an NPP is as a base load with the possibility of adjusting the power level depending upon the operating conditions of the NPP and the grid demand. Since NPPs have higher capital costs and lower fuelling costs than fossil-fuelled plants, and in most grids the nuclear share constitutes a small percentage (around 10% or less) of the total grid capacity, base load operation of NPPs is usually preferred. However, when the nuclear component increases and approaches the minimum demand, it is necessary that NPPs participate in load following operations to assist in efficient operation of the power system. In such cases the NPPs should be designed for a load following operation and their control systems must be able to execute the function.

A load following operation may be defined as any change in plant power in response to a change in network demand. This may be classified in the following categories.

Day-night cyclic load variations. These may occur daily, and the plant generally operates down to a 50% power level during a period of falling demand. Rates of change of power during such an operation usually range from 0.1% to 1% of nominal power per minute.

Load regulation. These load changes generally occur about ten times per hour and have magnitudes of less than ±5% of the rated capacity of the plant. They are usually prompted by the strategy of economic dispatch optimization.

Frequency control. These changes occur at random frequencies and represent typically less than 1% of the rated output of the plant.

Contingency operation. These power changes are usually prompted by an upset in the network or fault conditions. They may involve the provision of spinning reserves, including step-type and ramp-type power changes.

In a well organized high performance grid the grid frequency is controlled within a very narrow band (±100 mHz) during all operations except contingency operations, so that NPPs operating as base load stations are not subjected to disturbances and their control systems do not respond. However, during load following operations a satisfactory response from the control systems is essential. In a developing grid of limited capacity the random frequency variation may be well beyond the dead band (100 mHz), and it is necessary therefore to understand how the control systems of the NPP respond to the frequency variations. In a developing grid it is very unlikely that the NPP will be required to perform a load following operation; however, it does occasionally happen. It is relevant to understand the function of the control systems of an NPP in load following operations as well. The control systems of an NPP usually consist of the following subsystems:

- reactor power control or reactor control or a reactor regulating system
- turbine control system
- control system for the primary coolant pressure
- control system for the steam generator pressure (PWRs and CANDU PHWRs)
- control system for the water level of the steam generator/reactor.

Of these the first two, i.e. the reactor power control system and the turbine control system, form the interface between the grid and the NPP. The other control systems keep the important process parameters within operating limits. Discussion here is confined to the first two systems.

The reactor control system operates by sensing a mismatch between the power demanded (set) and the power generated by the reactor and adjusts the reactor power through changes in control devices, including control rods and liquid columns (CANDU PHWRs), by changing the recirculation flow (BWRs only) and by changing the poison (boron) content in the moderator. Controlling the power by changing

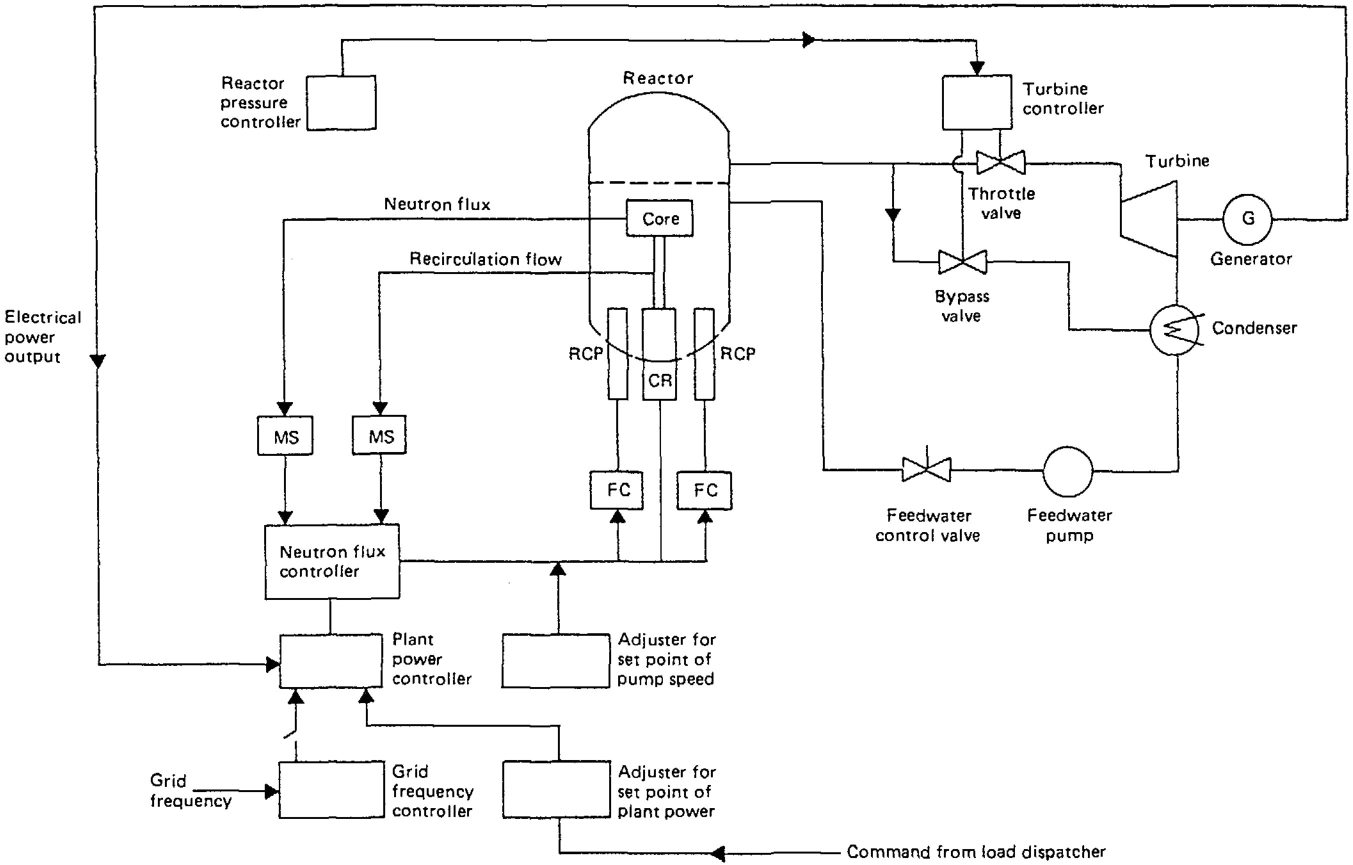

FIG. 5. Power control schematic of a typical BWR. (Courtesy of ASEA-ATOM, Sweden.)

the boron concentration in the moderator is slow, however. It is used in compensating slow long-term effects such as the loss of reactivity due to fuel burnup or buildup of poison due to xenon, and hence is not involved in short-term or transient responses.

The turbine control system adjusts the opening of the throttle valve and controls the steam flow into the turbine in order to match the turbine power with the power generated by the reactor or the power demanded from the generator by the grid. This is achieved by adjusting the governing oil pressure. The throttle valve opening is determined by the speeder/loader which controls the set point and the speed governor which acts through speed sensing. At steady state the throttle valve opening is governed by the set point, being subject to changes caused by variations in grid frequency. The opening is determined by the droop characteristic of the governor, which is usually around 4–5%. The turbine control system is also equipped with an adjustable load limiter which allows the opening of the throttle valve to a limited extent over and above the set point. This is in order to provide some reserve to the grid, as well as to limit the overdrawing of steam by the turbine, which would cause a serious mismatch between the power generated by the reactor and power drawn by the turbine, thereby leading to severe reductions in process parameters such as the primary coolant pressure, the steam generator pressure, etc.

The main control systems, i.e. the reactor power control system and the turbine control system, are co-ordinated on the basis of either a turbine-follow-reactor or a reactor-follow-turbine principle. The choice is based mainly on the dynamic characteristics and response of the overall system and the practically achievable response time of the control system. PWRs are generally operated in the reactor-follow-turbine mode to benefit from their inherent self-regulating characteristics. BWRs are always operated in the turbine-follow-reactor mode because of their unstable characteristics and the ease of altering the reactor power through control systems for the recirculation flow which have low time constants. CANDU PHWRs can be operated in either mode; however, they are usually, though not always, operated in the turbine-follow-reactor mode as base load stations.

Boiling water reactors

The working principle of the control system of a BWR is illustrated in Fig. 5, taken from Ref. [5], which may be referred to for a detailed description. During normal operation as a base load station the power output of the plant is determined by the set point of the reactor power and by the reactor's power control system. The turbine plant acts as a slave to the reactor. The throttle valve opening is adjusted according to the reactor power so that reactor pressure is maintained within close limits. Excess power is relieved by dumping steam into the condenser through bypass valves.

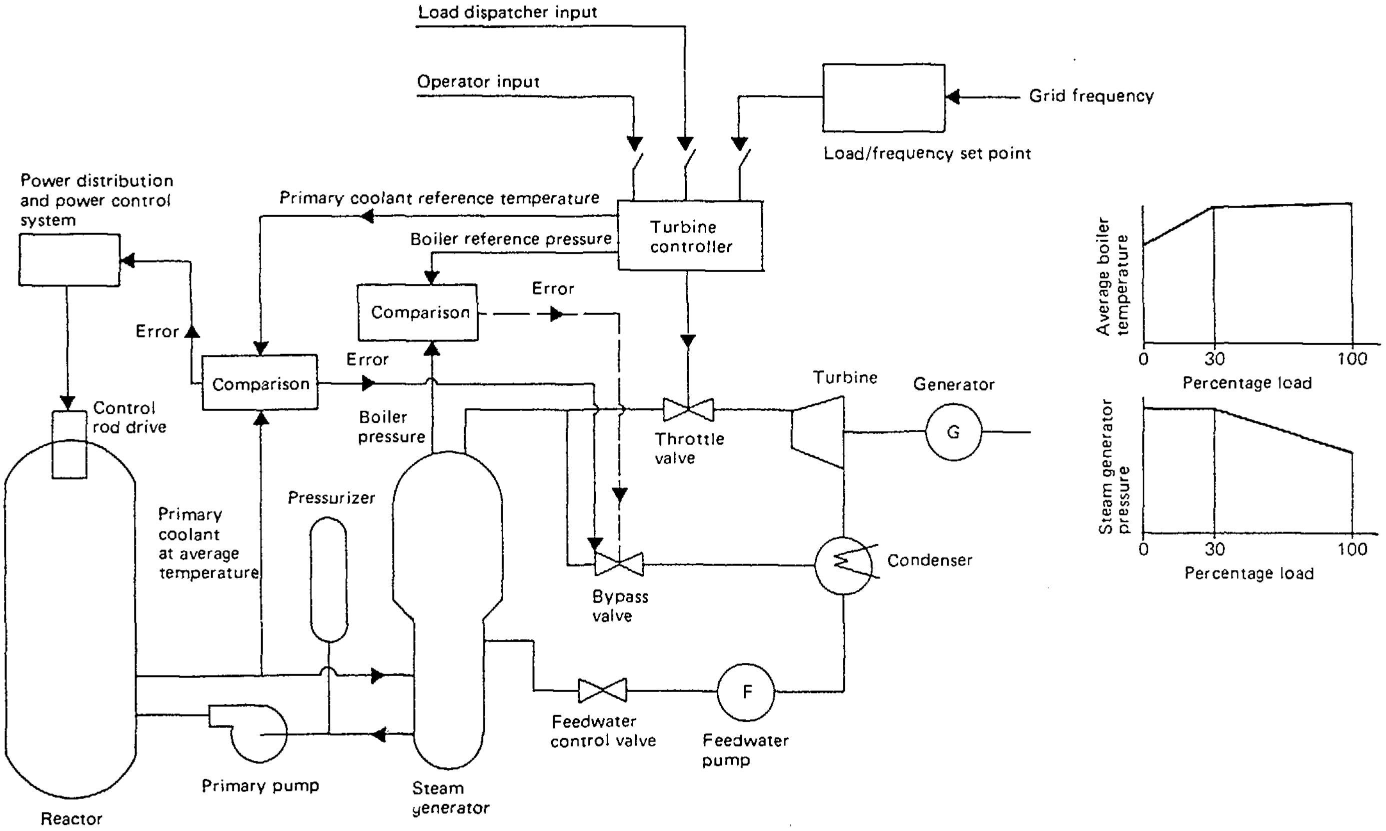

FIG. 6. A representative PWR power control system.

The reactor power is controlled through the movement of control rods and by varying the recirculation flow by changing the pump speed. In the high power range, 60% of nominal power and above, the power is generally controlled by adjusting the recirculation flow of the coolant, and can be varied at a maximum rate of up to 20%/min for speed control systems for the recirculation pump with low time constants, employing solid state frequency converters. Below 60% of the nominal power level, movement of the control rods is required and the power manoeuvring rate may drop to 1–2% per minute. In some designs the recirculation flow is controlled by control valves, and power change at the rate of 1% nominal power per second is possible between 75% and 100% of nominal power.

The reactor power control is executed by the master controller, which consists of a neutron flux controller, a plant power controller, a grid frequency controller and a pressure set point adjuster. Dynamic control of the reactor power is effected by the neutron flux controller, which limits the neutron flux to a level corresponding to 100% of the reactor power.

The plant power controller compares the electrical output of the power plant with the set point and changes the recirculation flow and maintains the power output close to the set point, provided that such a change in the recirculation flow is permitted by the control rod settings.

Changes in the power level are effected by way of changing the set point for the reactor power, either by the NPP operator or remotely by the load dispatcher through the load dispatch centre–NPP interface.

When involved in operations to control the grid frequency, the grid frequency controller computes the deviation from the set frequency and adjusts the set point for the reactor power within permissible limits.

The opening of the turbine throttle valve is not affected by the speed governor within the operating range of the grid frequency. The turbine output is reduced by the speed governor at frequencies of 51 Hz and above (for 50 Hz systems).

When operating in a grid of limited capacity, in which frequency deviations from the nominal are much wider than in a high performance grid, the power output of a BWR will not be affected by frequency deviations as long as the frequency is between 49 Hz and 51 Hz (for 50 Hz systems).

Pressurized water reactors

The working principle of the control system of PWRs is illustrated in Fig. 6, taken from Ref. [6], which may be referred to for a detailed description. PWRs are normally operated in the reactor-follow-turbine mode in high power ranges. However, in low power ranges they are sometimes operated in the turbine-follow-reactor mode. In the normal mode the reactor power is made to follow the turbine power closely. Changes in the set point for the turbine power output cause a change in the flow of steam through the turbine. The change in steam flow causes the pressure in the steam generator and the average temperature T_{av} of the primary coolant to change. PWRs are usually operated with a programmed T_{av} and steam generator pressure. A changed set point for the turbine power output generates the reference values for the steam generator pressure and T_{av}. The difference between the measured T_{av} and the reference T_{av} actuates the power control and the control system for the power distribution, as well as the steam bypass system. The measured steam flow is also used as an anticipatory signal for the power control system. The difference between the measured steam generator pressure and the reference steam generator pressure can also be used to operate the steam bypass system.

Changes in the reactor power are effected through the movement of control rods. This process is aided by the self-regulating characteristic of the reactor. Movement of the control rods introduces changes in the axial power distribution in the core. The local power distribution is closely monitored and movements of the control rods are restricted by the hot spot (power distribution) factor. The hot spot factor, or the power distribution, had been a constraint on the load changing capability of PWRs. Control strategies, including the use of quarter rods and grey rods, have been tried to reduce the size of the constraint. The successful use of grey rods for this purpose has been reported [7]. Changes in the reactor power are effected by changing the set point for the turbine power, done locally by the NPP operator or remotely by the load dispatcher through the interface between the load dispatch centre and the NPP.

Since the reactor power closely follows the turbine output power, it is subject to change when the grid frequency varies, prompting the speed governor to change the opening of the turbine throttle valve. In high performance grids, power changes induced in PWRs by small random fluctuations in the frequency can be compensated for by changing T_{av} without resulting in movement of the control rods. However, in a weak grid the greater magnitudes of random frequency fluctuations to be expected are likely to result in control rod movements. Such continual movements of small magnitude are likely to cause fatigue to the control rod drives. The limitations on the use of PWRs in controlling grid frequency arise from this factor as well as from the change in power distribution caused by the movement of the control rods.

CANDU pressurized heavy water reactors

The plant control system for CANDU PHWRs is shown in Fig. 7; Ref. [6] may be referred to for a detailed description. The control philosophy of the CANDU PHWR consists in keeping the pressure in the steam generator constant at all loads. In the normal (reactor-follow-turbine) mode, the turbine load is set to the desired value by the unit power regulator. The set point may be changed on demand by the operator or by the load dispatch centre. A change in the turbine load set point causes a change in the opening of the turbine throttle valve and a consequent change in the steam flow. The change in the steam flow leads to a change in the pressure of the

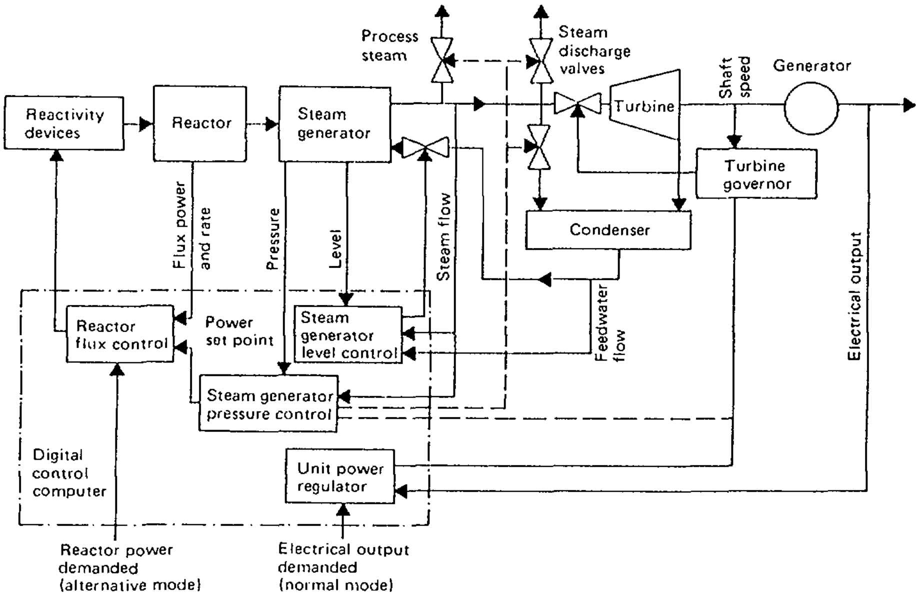

FIG. 7. Power control system of a representative CANDU PWR.

steam generator. The difference between the measured and the set pressures in the steam generator (the error signal for the steam generator pressure) adjusts the reactor power through the reactor regulating system and actuates the steam bypass system to keep the steam generator pressure at the set point.

In the alternate mode (turbine-follow-reactor) the operator fixes the set point required for the reactor power; the error signal for the steam generator pressure adjusts the opening of the turbine throttle valve and operates the steam bypass system to maintain the steam generator pressure at the set point. In the normal mode the steam flow is sometimes used as an anticipating signal for reactor power control.

The reactivity control devices, which are operated automatically by the reactor regulating systems of CANDU PHWRs, consist of (see Appendix V):

- Light water zone control absorbers for primary short term reactivity control;
- Mechanical control absorbers for augmentation of the negative value of the zone controllers;
- Adjuster rods for flattening the reactor flux and for augmentation of the positive value of the zonal control absorbers.

The temperature coefficient of reactivity of the coolant for CANDU PHWRs is very low. The feedback reactivity effect due to changes in the primary coolant temperature is negligible in CANDU PHWRs compared with that in LWRs. The neutron power is completely decoupled from the load disturbances. CANDU PHWRs can be operated in either the turbine-follow-reactor or the reactor-follow-turbine mode with equal ease. Neither mode offers any inherent advantages or disadvantages; the performance of CANDU PHWRs is determined by the responses and capabilities of the reactor regulating system and other process control systems, particularly the PHT pressure control system.

Random frequency fluctuations as experienced in weak grids call for corresponding power changes in the CANDU PHWR when operating in normal mode. The power change will normally be handled by light water zonal control absorbers and problems associated with the continuous small movements of the mechanical control rods in PWRs are non-existent in CANDU PHWRs operating in the alternate mode in a weak grid. The reactor power does not change, but the throttle valve opening becomes liable to change as a result of the speed governor and pressure control system for the steam generator competing between themselves.

4.12. THE LOAD CHANGE CAPABILITY

Most NPPs are at present operated as base load stations, and their preferred mode of operation is still the base load mode; however, when the nuclear component of generation approaches the minimum demand point of the grid they may be called upon to perform a load following operation. In grids of limited capacity, there may be occasions, although not regularly, when the NPP may be required to undergo the same operation. Most of the NPPs have some inherent degree of load following capability although not specifically designed for this purpose. The load changing capability of NPPs also determines their performance in the islanded mode of operation, where the burden of matching the generation with the load and maintaining the grid frequency within operating limits may largely rest on this capability.

The load changing capability of an NPP depends upon the following:

- Design characteristics, including the design of components related to fuel, high pressures and high temperatures in the nuclear steam supply system (NSSS) and turbine and other components in the balance of plant (BOP), and limitations arising from stresses induced by cyclic and transient pressure and temperature changes;
- The capability of the control system and the availability of reactivity reserve;
- The overall response and the availability of spinning reserve;
- The past operating state, which determines the buildup or decay of xenon;
- The current power level at which the load change is performed.

Reducing the power of an NPP to adapt to a lower load does not pose any serious problem, since excess power in the NPP can always be relieved by dumping steam into the condenser. A suitable dumping rate could be engineered so that important parameters such as the fuel temperature, the primary coolant temperature and pressure, the steam generator pressure, etc., are within operating limits.

Increasing the power of an NPP is limited by the available spinning reserve and the dynamic response time of the NPP. Making use of the spinning reserve entails calling upon the stored energy available in the steam in the steam generator/ reactor vessel and in the primary coolant initially and bringing up the reactor power by increasing the reactivity through the action of the reactor's power control system. In PWRs steam generators are operated at a programmed pressure, which increases with decreasing reactor power. The energy stored in the steam generators in these reactors can be utilized as the first source of reserve energy to provide additional power input to the turbine by opening the throttle valve. However, some PWRs are designed to operate with once-through steam generators, and the stored energy reserve available in such boilers is very much less than for drum-type recirculation boilers. As more steam is withdrawn from the steam generator, its pressure falls, which is as for the pressure programme for PWRs. The fall in pressure in the steam generator is accompanied by a fall in the temperature and pressure of the primary coolant. The rate and magnitude of the fall depend upon the rate and magnitude of the load change and the power level at which the load change was initiated. The rate and magnitude of load changing are therefore limited by the capability of the control system of the NPP, particularly the pressure control system for the primary coolant. The initial part of the transient caused by the load change is met by the energy stored in the steam generator; subsequent matching of the power to the load must be effected by the power control system of the reactor. The overall dynamic response time (the time constant) has a considerable influence on the rate of increase of power of the NPP. The time constant between the turbine output power and the change in the set point of the reactor power for PWRs and CANDU PHWRs of standardized unit sizes above 440 MW(e) is around 30 seconds or more, whereas in the case of BWRs of a corresponding size, having a direct cycle, it is less: around 20 seconds or more. BWRs also provide for the utilization of the energy reserve stored in the steam in the reactor vessel, by opening the throttle and temporarily depressing the pressure set point. However, such action is normally followed by a quick change in the recirculation flow. CANDU PHWRs operating with a constant pressure in the steam generator do not provide a spinning reserve in the form of stored energy. While operating in the normal (reactor-follow-turbine) mode, the loading rate will depend upon the capability of the regulating system of the reactor, and on the pressure control system.

The rate of rise of power is limited by the restrictions in the movement of the control rods imposed by the associated distortion of the axial flux profile. The change in loading demands a corresponding increase of reactivity at the required rate. The concentration of xenon in the reactor and the reactivity reserve available with the control rods, which depends upon past operation, will determine the movements of the control rods within the limitations imposed by the deviations in the axial flux distribution. In PWRs, where short-term changes in power are mostly effected by way of the control rods, these factors may seriously limit the loading rate. It has been suggested that the reactivity may be increased by reducing the temperature of the primary coolant, which would not affect the neutron flux distribution in the reactor core. This may be particularly useful at the end of the fuel cycle [8].

The problem of flux distribution is somewhat alleviated by the addition of burnable poisons such as gadolinium to the fuel, as is done by some BWR manufacturers [5]. The flux distribution is not affected when a power change is effected through a change in the recirculation flow. Control rod movements do not affect the flux distribution in CANDU PHWRs as much as in LWRs. For large CANDU PHWRs, the zonal power oscillations caused by xenon are taken care of by a separate zonal control system involving the movement of light water columns.

Pellet–clad interaction (PCI) in the fuel also limits the loading rate of LWRs, particularly during the first rise of power after refuelling. Fuel for CANDU PHWRs, being of a collapsible clad design, is not affected by PCI, and the loading rate is limited by the thermal stresses in the clad, as for other types of reactors.

Stresses induced in the components of NSSS and BOP, especially the turbines, limit the loading rate.

Subject to limitations imposed by the turbine, NPPs can safely withstand a step load change of 10%. However, the system must stabilize for about 5 minutes before the NPP can be subjected to another load change.

All NPPs can comfortably follow scheduled load following requirements (0.1–1% of nominal power per minute). Higher loading rates of 5% per minute to 10% per minute for PWRs, 20% per minute for BWRs and 12–60% per minute for CANDU PHWRs can be achieved, depending upon the magnitude of the change, current operating power level, the operational history of the NPP, and the permissible turbine loading rate, particularly for CANDU PHWRs.

4.13. THE EFFECT OF TRANSIENTS ON NPP COMPONENTS

Disturbances originating in the grid induce transients in the NPP, which result in changes in temperature and pressure in the subsystems of the NPP and induce thermal and mechanical stresses in the components of the NSSS and the BOP. Large disturbances which result in separation of the grid and the NPP (load rejection), turbine trip and reactor trip put severe stresses on the components of the NPP. In islanded operation the NPP may be subjected to severe load changes. In addition to these disturbances, load following operations by an NPP subject its components to cyclic stresses and fatigue.

The cumulative effect of these stresses may be to cause damage to critical components such as the fuel, the control rods, joints in the primary coolant pipe, etc. [3].

Large stresses induced by reactor scrams at full power affect the guaranteed life of the fuel, the primary structure, the control rods, etc. Manufacturers of NPPs guarantee their performance during their lifetime of 30 years within a transient budget of 300–400 full power scrams, for the primary structure (see Appendix IV).

In a grid of limited capacity it is unlikely that the NPP will be required to perform load following operations under normal circumstances. However, variations in grid frequency may induce transient power changes in the NPP fairly frequently. Operation in the islanded mode and the house loaded condition is also expected to be more frequent. Some house loading operations may be unsuccessful and lead to a reactor scram. Whether the operating life of the NPP will be reduced or critical components will be damaged is difficult to predict; however, closer surveillance of critical components and maintenance work may be inevitable when NPPs are operated in such a grid environment.

4.14. THE PROTECTIVE SYSTEM OF THE REACTOR

The protective system of the reactor, which automatically shuts the NPP down in the case of abnormal or emergency conditions, is engineered with sufficient reliability to maintain the probability of an accident in any one year below a stipulated value. An automatic protective system should be designed such that the probability of failure to shut down on demand following a loss of grid supply causing a loss of coolant flow shall be 1 in 10^6 [9]. If the probability of the loss of a grid exceeds 1 per year, which is quite likely for grids of limited capacity, there is a corresponding increase in the accident probability per year for the NPP operating in such grids. If it is desired to maintain the probable hazard period[3] in accident years per year within the stipulated value, either the reliability of the protective system must be enhanced or the probability of loss of grid supply must be reduced. Since the protective systems of the reactors of NPPs are engineered for maximum reliability through sufficient redundancy within reasonable cost, it is rather difficult to enhance their overall reliability by improving the component reliability without a disproportionate cost increase. Increasing redundancy also leads to an increased probability of spurious trips. Under these circumstances, NPPs operating in grids of limited capacity are subjected to an increased hazard period until the probability of the loss of grid supply can be reduced by suitable measures relating to the grid.

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[3] Probable hazard period is defined as the number of incidents of loss of coolant flow due to loss of grid supply per year multiplied by the unavailability of the reactor protective system in years per year.

4.15. THE EMERGENCY ELECTRICAL POWER SYSTEM

The total loss of Class IV power is one of the postulated incidents which the NPP has to withstand through the appropriate action of the reactor protective system and the engineered safety system. While the reactor protective system shuts the reactor down, the engineered safety systems cater for heat removal from the reactor and keep the NPP in a safe shutdown condition. The emergency electrical power system (EPS) provides the power for the pumps needed to circulate cooling water through the core, and for injection and pressurizing pumps to maintain proper conditions of the coolant during operations such as cooldown and crash cooldown of the primary coolant; and it provides power to instrumentation and control systems and to other services needed to maintain the NPP in a safe shutdown condition until the grid supply is restored. The EPS or on-site power supply system is not designed to meet the requirements of startup power (the power needed to run the circulation pumps for the primary coolant) for the NPP. The EPS consists of diesel generators and a battery bank with AC–DC and DC–AC converters.

The on-site power supply system is designed to be reliable enough to match the probability of grid failure (the loss of off-site power) so as to maintain the probability of a total loss of power, both off-site and on-site together, and hence the probability of a loss of forced cooling for the reactor, within acceptable limits.

The lower reliability of a grid of limited capacity will require a greater reliability of the on-site power system to keep the combined probability of a total loss of power (station blackout) at the NPP within acceptable limits.

This may call for the provision of additional redundancy in diesel generators, thereby increasing the investment, and more frequent testing of diesel generators and other equipment in the on-site power supply system. The operating power level of the reactor might need to be reduced during the period when the main equipment such as diesel generators in the on-site power supply system are in maintenance if the redundancy or the capacity of the diesel generators has not been increased.

The EPS or on-site power supply system is covered extensively in IAEA Safety Guide No. 50-SG-D7 (NUSS programme) [10], which may be referred to for specific information.

5. INTEGRATION OF NPPs WITH THE GRID

Operating experience with NPPs in weak grids indicates that inefficiency in such operation arises from the inadequacy of the grid and the incompatibility between the grid and the characteristics of the NPP. These problems should be tackled at the planning stage rather than at the operational stage of the NPP. Inadequate evaluation of the problems may necessitate retrofitting at considerable expense to obtain satisfactory performance from the NPP.

Problems in the successful integration of an NPP with a grid are similar to those encountered in conventional power system planning. The techniques and methodologies employed in power system planning can also be used for the effective assimilation of a nuclear component. However, for realistic results the techniques and methodologies must take into account the characteristics of the NPP. The requirement imposed upon the grid for the safe and economic performance of an NPP has to be given full cognizance, and the implications of shortcomings and deficiencies in the grid must be understood.

5.1. PLANNING FOR AN NPP

The methodologies involved in planning for an NPP are akin to those used in planning for the introduction of new thermal generating units. It is quite natural for the prospective NPP owner to look for the most economic choice. NPPs have high capital costs compared with fossil-fuelled stations owing to their complex in-built engineered safety features. Economies of scale have prompted the development and standardization of NPPs of higher unit sizes. At present, the proven NPP types commercially available for export include PHWRs, PWRs and BWRs in unit sizes of 440–1300 MW(e) [11]. Designs for smaller unit sizes, e.g. a 300 MW(e) CANDU PHWR, are available. However, these have yet to be proven in construction and operation.

The economic incentives afforded by these standardized units, which, as well as lower capital costs, include more straightforward construction and licensing, encourage the prospective owner of an NPP to consider standardized units as the prime choices. The planning process for NPPs therefore reduces to the rigorous exercise of finding out how these units can be smoothly integrated into the power system. The standardized sizes and types also offer a fairly wide choice.

However, the choice of size and type of NPP may depend upon many factors apart from its suitability with regard to the grid requirements. The economics of nuclear power vary from country to country and sometimes a lower unit size may also be a viable solution.

The steps involved in planning for an NPP are as follows:

- assessment of grid characteristics
- assessment of characteristics of commercially available standardized units of NPPs
- assessment of the duties of the NPP in the grid
- assessment of the interaction between the characteristics of the NPP and the grid
- choice of type and size of NPP most responsive to the demands of the grid and most adaptable in the grid environment
- incorporation of suitable measures for cost effectiveness in the NPP and the grid.

5.1.1. Assessment of grid characteristics

The object of an assessment of grid characteristics is to obtain a clear picture of the grid environment in which the proposed NPP is likely to be operated. This includes normal steady state operation as well as operation under disturbances in the grid, such as transmission line faults, loss of generation, etc. There is a considerable time gap (around 10 years) between the commencement of planning for an NPP and the beginning of its operation in the grid. The grid characteristics may change considerably during this period. However, there is also enough time available to incorporate appropriate changes in the grid for the smooth integration of the NPP.

Methods involved in the assessment of grid characteristics include the following:

- Monitoring and recording of relevant data during normal operation;
- Monitoring of relevant data during faults and abnormal situations;
- Assessment of the frequency of incidence of faults;
- Assessment of the performance and reliability of control and protective systems;
- Prediction of demand patterns for the grid as well as for neighbouring interconnected grids;
- Realistic assessment of the growth of generating capacity, apart from NPPs, in the grid and interconnected grids, based on past experience;
- Realistic assessment of the targets achievable in network expansion and network protection.

Normal grid operating data consist of:

- Daily, weekly and monthly load variations;
- Daily random load variations, their magnitudes and the number of cycles;
- Frequency variations;
- Voltage variations at selected points, particularly at the proposed connection point of the NPP;
- Power flow through the tie lines.

The current normal operating data give some idea of the grid environment (frequency and voltage variation) to which the proposed NPP may be subjected. They may also indicate the role of the NPP in the power system: whether it can be operated as a truly base load station, or whether it has to participate in scheduled load following. The data will also show the deficiencies in generation, the need to match peak demand (underfrequency operation), the need for additional cyclic generating capacity, the need for improvement of the automatic generation control (AGC) scheme, etc.

Data concerning operating states bear on the following:

- The frequency of transmission line faults;
- The performance of the grid protection system in clearing the fault, as a percentage of successes or failures out of total incidents, based on real experience;
- The voltage disturbance observed during faults and their subsequent clearance;
- The frequency of incidents involving loss of generation;
- The rate of frequency drop for the loss of the largest generating unit;
- The lowest frequency experienced during the loss of the largest generating unit;
- The time taken to recover to nominal frequency;
- The frequency of severance of interconnection;
- Disturbances leading to loss of interconnection;
- Disturbances caused by loss of interconnection in the grid in which the NPP is proposed to be commissioned;
- The frequency and duration of grid collapse.

These data give a picture of the frequency and scale of disturbances in the grid. They also help in assessing the capability of the grid and its control system to withstand the disturbances. Furthermore, they help to identify any inadequacies in system design, sizing of the interconnection, tie line control, spinning reserve, automatic generation control, load shedding and grid protection systems. System characteristics such as grid stiffness and inertia constants can also be determined. It is quite likely that these data may not be readily available. Special tests may be performed to obtain the data wherever possible without causing serious upset condition in the grid. In the event that tests cannot be performed, simulation studies should be conducted to obtain as close an idea of the real situation as possible.

Several simulation studies must be made of the power system on the basis of data on the current state of the grid and a realistic assessment of the expected state when the NPP goes into operation. The purpose of the simulation studies is to arrive at a realistic grid scenario including normal and abnormal operating conditions. These studies include the following:

- Load flow studies at various power levels;
- Transient stability studies for fault conditions;
- System dynamic studies for the loss of the largest generating unit (probably the proposed NPP) and the snapping of tie lines.

The results of the simulation studies, depending upon the approximations used in the modelling and the accuracy of the input, reveal the grid conditions the NPP would probably face during normal and disturbed operating conditions. They also indicate the stability problem for the grid if the proposed large NPP is lost. The inadequacies in interconnections, tie line control, automatic generation control and load shedding will also be brought to light in an at least partly quantitative manner, providing the necessary basis for grid reinforcement.

It is thus possible to prepare a data sheet showing the characteristic features of the grid. It might not be entirely accurate but should be fairly representative. Such a data sheet is presented in Appendix VI. Methods of monitoring and recording grid data and the scope of modelling have been presented in Ref. [3].

5.1.2. NPP characteristics

After determining the characteristics of the grid in which the proposed NPP is supposed to operate, the prospective owner should approach vendors for information about their products. It is always advisable to prepare a questionnaire seeking specific information which is relevant to the particular grid environment and duties of the proposed NPP. Such a questionnaire would typically request information on the following:

- The available unit size;
- The preferred mode of operation, the base load scheduled, load follow, the network frequency control, etc.;
- The capability of operating in the load follow mode;
- The load change capability;
- The ability to come back to house load and sustain house load operation;
- The minimum operating power, while at house load;
- The ability to withstand full load rejection without the reactor tripping;
- The ability to withstand a turbine trip without the reactor tripping;
- The time to return to full power after a trip;
- The run-back or power set-back capability;
- The permissible frequency and voltage band for normal operation;
- The extent of limited operation under off-normal frequency and voltage conditions;
- The permissible voltage and frequency band for the normal operation of auxiliaries.

A typical questionnaire is described in Appendix VII. In a low performance grid the frequency of loss of Class IV power supply can be expected to be quite high, as is borne out by operating experience. It is therefore necessary to subject the emergency electric power supply (EPS) of the NPP to a thorough evaluation. All postulated emergency conditions, including small, medium and large LOCA coupled with loss of Class IV supply, should be analysed. Operations such as crash cooldown in emergency conditions and their effectiveness when Class IV supply is lost should be analysed. These analyses should be carried out taking into account the probability of a partial failure of the EPS and assuming that some part of it could be under maintenance when the accident occurs. These analyses can be performed effectively using fault tree and event sequence diagrams. If the probability of a total loss of power (a station blackout), taking into account the higher probability of the loss of Class IV power for weak grids, seems to be rather high, reinforcement of the EPS may be necessary. The adequacy of the EPS cannot be assessed by means of questionnaires and answers. Enhancing the reliability of the EPS to compensate for the increased frequency of the loss of Class IV power might be a costly proposition. A prospective NPP owner should discuss this topic in detail with the vendor as well as the licensing authority to ascertain the risk and to find a cost effective solution.

In a grid of limited capacity the NPP is likely to be subjected to a large number of transients of limited magnitude caused by random frequency changes. The number of severe transients caused by phenomena such as load rejection is likely to be considerably greater. The NPP may not survive all of these large disturbances without tripping. Such transients cause severe stresses in the components of the NPP. A large number of transients of small magnitude might prompt a large number of movements to actuators of controllers, throttle valves or control rods and subject them to fatigue. Severe stressing caused by more load rejections and fatigue caused by many small but discernible disturbances might reduce the life of NPP components and might require increased surveillance and maintenance of some of the components. A prospective NPP owner should discuss the matter with the NPP vendor in depth and in detail and should provide for means of surveillance of the crucial components suggested by the NPP vendor. A schedule for in-service inspection and necessary maintenance should also be worked out in consultation with the supplier of the NPP.

5.1.3. Assessment of the role of the NPP in the grid

The NPP owner, together with the authorities for the power system and other utilities contributing to the total power generation in the grid, should decide together on the role of the NPP in the grid. The high capital costs and low fuelling costs of NPPs tilt the option towards base load operation. The authorities should therefore arrange for enough cyclic generating capacity and adjust the droop of the governors of other stations so that the NPP can operate as a true base load station. However, there might be occasions, although rare, when the NPP may be subjected to load following operation to a limited extent. In the islanded mode of operation the NPP is likely to be subject to considerable load fluctuation. It is desirable, therefore, that the NPP should be capable of performing load following operation to a certain extent, especially so when intended for operation in grids of limited capacity.

5.1.4. Assessment of the interaction between the NPP and grid characteristics

With a fairly representative picture of the grid in which the NPP is to operate and a knowledge of the characteristics of the various types of NPPs obtained from vendors, the task remains to assess the interaction between them. This indicates to what extent the grid environment deviates from that in which the NPP is normally supposed to operate. It also helps to point out possible measures to modify the grid and NPP characteristics in a cost-effective manner, to obtain the optimum performance of the NPP under the existing conditions. Interaction between the NPP and grid characteristics has been discussed in detail in Section 2 and also in Ref. [3].

Of specific importance are the following:

- The effect of random frequency variations in the grid on the NPP;
- The effect of major grid disturbances such as transmission line faults, load rejection, etc., on the NPP;
- The effect of load fluctuations on the NPP under the islanded mode of operation;
- The effect of a scheduled outage of the NPP on the grid;
- The effect of a forced outage of the NPP on the grid;
- The requirement of the quality of the grid supply for startup and running of the NPP.

5.1.5. Choice of the type and size of NPP most responsive to grid demand and most adaptable to the existing grid environment

After evaluating the interaction and interrelation between the characteristics of the grid and those of commercially available NPPs, the next step is to arrive at a proper choice. It is very unlikely that a grid of limited capacity could successfully absorb the NPP without sacrificing performance, unless remedial measures in the grid and NPP are incorporated. NPPs which permit modifications in the most cost effective manner and place the minimum demand on the grid will naturally be preferred. However, it should be borne in mind that there are many other factors besides the adaptability of the NPP in the grid which influence the choice.

The choice of size of NPP is made on the basis of economic considerations, and the factors considered and methods adopted are the same as for the introduction of large fossil fuelled stations into a power system. However, the best economic performance is obtained from the NPP if it is operated at nominal power most of the time, owing to its high capital cost and low fuelling cost; operation at lower power, as in the case of the NPP carrying out scheduled load follow operations, will affect the economics. Besides, the NPPs, particularly LWRs, require scheduled outage periods of 4–8 weeks for refuelling after 12–18 months of operation, over and above time lost in forced outages and for unscheduled maintenance. Economies of scale sway the choice towards NPPs of large unit size. Introduction of NPPs of such large unit size calls for substantial reinforcement of the grid to maintain the quality and security of its performance. Such measures are likely to need considerable investments. Choice of the unit size will depend upon the following factors:

- The creation of additional reserve to cater for scheduled outages of the NPP for refuelling;
- The creation of spinning reserves for restoration of the system frequency after the NPP is lost owing to forced outage;
- The frequency drop permitted as a result of loss of the largest generating unit (NPP). This can be around 1 to 1.5 Hz during peak load and 1.5 to 2 Hz during light load. However this is left to the authorities for the power system concerned;
- The reinforcement of tie lines and implementation of proper tie line control;
- The implementation of appropriate and reliable AGC and load shedding schemes.

The unit size is therefore to be chosen on the basis of both a cost–benefit analysis of the economies of scale for the NPP and the investment requirements for grid reinforcement.

The choice of NPPs of smaller unit size might turn out to be economic from an overall perspective, although the choice may be uneconomic with regard to capital investment for the NPP.

The choice of type of NPP will depend upon many factors apart from its adaptability to grid requirements. From the point of view of the grid, the following factors are of prime consideration in the choice of NPP:

- The range of voltage and the frequency band within which the NPP can be operated at nominal power;
- The immunity of the NPP to random frequency changes occurring in the grid;
- The ability to withstand load fluctuations encountered in the islanded mode of operation without tripping;
- The ability to survive full load rejection and successfully to revert to and sustain house load operation until the grid conditions are suitable for resynchronization.

These factors constitute the criteria for selecting a type of NPP for successful operation as a base load station in a grid of limited capacity. These factors provide only general guidance, and the choice has to be made in the light of the characteristics of the grid concerned.

5.1.6. Incorporation of suitable measures in the grid and the NPP

In a grid of low performance or limited capacity, the standards of the grid characteristics are lower than for high performance grids into which NPPs of large unit size have been successfully integrated. It is also quite unlikely that NPPs of standardized unit sizes would operate as successfully without incorporating some remedial measures into the grid and the proposed NPP. It is always better if these measures are taken before the NPP is commissioned in the grid, since retrofitting may not be cost effective. However, some of the measures could be introduced after the NPP is commissioned and some operating experience has been gained.

5.1.6.1. Measures in the grid

The shortfall in the expected performance of a grid of limited capacity arises mostly from its inability to match power generation with peak demand. Other factors include the lack of proper AGC, load shedding schemes, voltage controlling devices and the grid protection system, as mentioned in Section 2.

The shortfall between power generation and peak demand has its origin in the planning process. The planning process includes the proper assessment of the maximum demand and the availability of generating capacity as well as the amount of power exchange with the neighbouring grids. The proper assessment of capacity factors for the plants is also essential for predicting the availability of generating capacity, with a sufficient degree of confidence. For the effective functioning of the power system, it is necessary that the authorities in charge of generation and those in charge of transmission, distribution and control participate in the planning process. If this is not done the connected load may exceed the available peak generating capacity and generation capacity will fall below the maximum demand[4]. The generating capacity available should therefore be predicted with a degree of caution. The availability of power generation from hydro stations which depend upon seasonal rainfall should be predicted with care. The power generation available from an NPP should be estimated in full consideration of its operating characteristics. The first rise to nominal power after commissioning or refuelling takes about four weeks at least. This includes fuel conditioning at various power levels for LWRs. A licence for operation at full power is usually granted in stages upon demonstration of safe operation at various power levels. Any inadequacy revealed, particularly in safety or safety-related systems, would need re-examination, modification and clearance from the licensing authorities. This is likely to be a time-consuming process, resulting in a delay in the availability of power from the NPP at the nominal level. Proper assessments should be made of the forced outage rates of all generating units, including that of the proposed NPP, especially during its operation in the first year (see Section 2). Unrealistic assumptions of target availability for generating units which are not achievable will lead the authorities of the power system to permit more load to be connected to the system. The result of this will be shortfall of generation with respect to demand. If the planning is unrealistic, the grid environment in which the NPP would be operating might be quite different from that originally planned, and its performance might be substantially affected.

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[4] Maximum demand = connected load × diversity factor.

The planning process must include the measures needed to integrate the NPP successfully into the grid, taking fully into consideration its operating characteristics. These include generation scheduling, maintenance scheduling, tailoring the peak demand and other measures given in what follows.

Generation scheduling

Generation scheduling is done by allocating the amount of generating capacity to each generating unit at various loads for optimum economic performance. The scheduling strategy should be agreed between the owners of the generating units and the authorities responsible for transmission and distribution. Introduction of an NPP, particularly one of large unit size designed to operate as base load station, might require some of the units operating on base load duty to perform scheduled load following operations. The generation pattern must therefore be rearranged among the authorities concerned. Normally in a power system containing nuclear, thermal and hydro stations, nuclear and run-of-the-river hydro units are operated at their nominal power as far as possible because they have high capital costs but low (for nuclear) and no (for hydro) fuel costs, and thermal stations perform duties of scheduled load following. In addition, storage-type hydro stations (if available) are used to meet sudden peaks in demand, as well as for grid frequency control. In a grid where there is not enough cyclic generating capacity in the form of thermal stations, the introduction of an NPP of large unit size will call for scheduled load follow operations, either from the NPP itself or from the hydro units. Hydro units which depend upon seasonal rainfall for their power may not be readily usable for scheduled load following operation for economic reasons and owing to irrigation constraints. Generation scheduling in such cases must be worked out in consideration of the economics and the limitations in scheduled load following operation for the NPP and the hydro stations.

Maintenance scheduling of generating units

LWRs operate on the basis of off-load refuelling. To reduce downtime, in-service inspection and major maintenance work are done during refuelling. LWRs thus have more or less fixed outage schedules and there is not much flexibility for changing the date for shutdown for refuelling. However, some degree of flexibility is offered by manufacturers of LWRs by permitting coast-down operation, in which the NPP is operated at gradually reduced power for the stretched out period (see Section 4.1). This facility is attractive for the operation of NPPs in a grid of limited capacity, and permits the generating units in the grid some flexibility in scheduling outages for maintenance. The prospective owner should discuss the implications of coast-down operations with the NPP vendor. CANDU PHWR units, which operate on the basis of on-power fuelling, offer considerable flexibility in scheduling outages for maintenance.

The scheduled outage of an NPP of large unit size causes the loss of a large amount of power from the grid for a considerable period of time. Maintenance outage of the generating units should be properly planned to compensate for the loss of generation of the NPP. Sometimes the shortfall in generation is made up by borrowing power from a neighbouring grid through an interconnection. To ensure the availability of such power, maintenance outages of the units in the interconnected systems should be planned in a co-ordinated manner. The difficulty is compounded when the outage of the NPP coincides with the lean generation period of hydro units dependent upon seasonal rainfall. Forced outages of generating units beyond the figure assumed in planning add to the shortfall in power generation. A shortfall in generation below peak demand would lead to a sustained power cut, and embarassment for the utilities, or sustained underfrequency operation for the power system, definitely undesirable for the power system from an operational point of view.

In planning for the introduction of an NPP of large unit size into a grid of limited capacity, care must be taken to plan the outages of other units so that enough generating capacity is available to meet the peak demand. Underfrequency operation may be resorted to under peak load; however, the limit of the underfrequency should

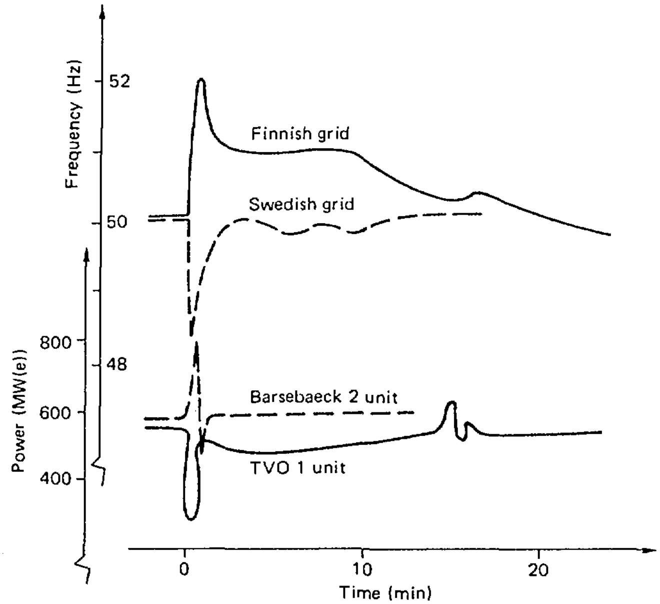

FIG. 8. Transient frequency change and power oscillation in an NPP caused by loss of interconnection in a high performance grid.

be chosen after considering the effects of disturbances such as loss of generation and loss of tie lines. For a grid of limited capacity it may be difficult to make up completely for the loss of an NPP of large unit size through scheduled outage without providing for additional reserve to meet peak demand in the power system and the borrowing of a larger amount of power through an interconnection, which might or might not be available. Such measures, particularly the provision of generating capacity to meet peak demand, might require considerable investment. In such cases, rather than using a single unit of large capacity, small grids should rather employ two units of half the capacity, whose refuelling outages could be staggered. The probability of the forced outage of two units at the same time is considerably less than the probability of the outage of one large unit.

During the outage of an NPP, its staff, particularly the maintenance staff, would be under pressure to bring the unit on line as fast as possible. The larger the unit size, the greater would be the pressure to beat the clock. Under these conditions it is quite likely that before restarting the NPP, some of the tests which are not obligatory for meeting the licensing requirements but are none the less important for the efficient running of the plant are omitted or reduced in duration, resulting in forced outages. Furthermore, such pressure on the maintenance staff is very likely to tell on their performance, as well as on the performance of the NPP in the long term.

Tailoring the peak demand

In a grid of limited capacity the available generation more often than not falls short of the peak demand; the possible reasons for this have already been described. While utilities should make every attempt to increase the generating capacity to meet the demand at all times, constraints on their so doing may force them to attempt to flatten the load curve to bring the peak demand closer to the maximum generation available. If the terrain of the area in which the power system is operating permits the operation of pumped storaged units, the economic viability of such units should be seriously assessed, since such units can provide assistance to generating units in meeting peak demand. Shifting of the load away from the peak demand period must be done by administrative measures as well as by the introduction of differential tariffs that include incentives as well as penalties. However, such measures would have many socio-economic implications and could only be introduced with the consent and active co-operation of domestic consumers, industry, government and other agencies concerned.

Interconnection

The strength of high performance grids lies largely in the extent of their interconnections. Such grids are usually highly interconnected and allow an exchange of power at all times so that the optimal use is made of generation in the grids and the availability of adequate power for contingencies is ensured through interconnection. Effective tie line control ensures smooth functioning of the interconnected systems and provides for islanding of the grids during emergencies. However, such situations rarely occur in high performance grids, except in the event of faults on the tie lines. Results of the severance of interconnection in high performance grids are shown in Fig. 8[5].

In contrast, in a low performance grid there may be no interconnections, and even when they do exist, tie lines might be of inadequate capacity and tie line controls inefficient (see Appendix II). Introduction of an NPP, particularly one of a large unit size, into a grid requires fortification of the interconnections of the system and of its controls.

A comparatively small grid might not absorb all the power from an NPP of large unit size; some of the power generated by the NPP might be exported to a neighbouring grid. During scheduled outages of the NPP, the grid might require the importing of a large amount of power from the neighbouring grid.

During tripping of the NPP a large reverse flow of power from the neighbouring grid would tend to occur. If the tie lines are not designed to carry such power, they would be tripped. If such a large outflow of power could not be tolerated by the neighbouring grid, tie lines would be tripped there as well (see Section 2.4).

The introduction of an NPP into a small grid therefore requires the proper engineering of tie lines and their controls so that islanding does not occur frequently and if it does occur it is engineered through controls to avoid collapse of the complete interconnected system.

The tie line size or the capacity for system interconnection is derived from the following:

- Studies of load flow under various steady state operating conditions of the interconnected grids;
- Transient power flow through the tie lines under the loss of the largest unit in each of the interconnected grids at the same time.

For a reasonably stable performance, the capacity of the system interconnections should be at least 10% of the installed generating capacity of the smaller of the two connected systems.[6] However, if a large NPP is introduced into a small grid, the interconnection capacity needed may be much larger.

Tie line controls limit the power flow through the tie lines to within the design capacity as well as performing islanding to prevent the interconnected system from cascade tripping as a result of a large disturbance in one of the systems.

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[5] Grid disturbance 13 Jan. 1979 (separation of Nordel grid into two parts); grid frequencies and examples of plant output.

[6] From experience in the USA and in Nordel.

These controls are based on the following:

- Underfrequency for preventing total system collapse;
- The magnitude of the power flow;
- Reverse power flow in case the borrower does not wish to export power under any circumstances and is solely concerned with the protection of its own system; this is particularly important when the management of the power system is not well co-ordinated.

The capacity of an interconnection between two systems and the implementation of a control strategy must be arrived at by discussions between the authorities of the respective grids. These should have the following objectives:

- Tie lines should be of sufficient capacity to be able to export the power of the NPP to the neighbouring grid.
- They should be of sufficient capacity to be able to carry the power required to be imported from the neighbouring grid when the NPP is down for refuelling or maintenance (long shutdown).
- They should be of sufficient capacity to handle the transient power flow when the largest unit in each grid trips at the same time.
- Islanding should be a last resort, when the collapse of the total interconnected system cannot be averted. If the grid containing the NPP were islanded on an NPP trip, it is very unlikely that it would survive, and total loss of Class IV power at the NPP would occur.
- Islanding should be done at a frequency higher than the isolation frequency of any generating unit operating in the interconnected system.
- Such islanding operations should preferably be automatic.

Islanding

During disturbances in the grid it may be necessary to break up the grid into islands, when it is no longer possible to sustain operation of the grid in the interconnected mode. In a highly interconnected system the islanding operation is avoided, except in the event of faults in the interconnecting lines. High capacity and redundancy of the interconnecting lines reduce the probability of such incidents to a negligible value. A disturbance caused in any of the grids is tackled by load shedding in all the interconnected grids to sustain the operation of the interconnected system. Such an operation is feasible because of a concerted arrangement of operation and control of the power system between the authorities concerned with the power system. It should be noted that generally an interconnected system of operation with a proper arrangement for load shedding has a better chance of survival than operation in an islanded mode. This practice is adopted in the interconnected European power system. Measures should be taken, including generation control and load shedding, so that islands remain stable and do not collapse. Islanding a part of the grid that includes an NPP should be planned carefully beforehand, taking into consideration the operational characteristics of the NPP, the characteristics of other generating units in the island, the load and its fluctuation in the islanded section. If the NPP is designed for base load duty and has a limited capability for load change, it is highly desirable that the NPP power level be kept at maximum and fluctuations in its power generation be kept to a minimum. This requires provision of an adequate amount of base load in the islanded section. If a pumped storage system is already available, its possible use as a base load during such an islanded mode of operation should be considered. The islanded section should preferably have generating stations which can handle the load fluctuations so that the frequency in this section can be kept within permissible operating limits.

During islanded operation, the NPP may be in a part where the power generated is in excess of the connected load or in a part where the generation is lower than the connected load. In the former case a quick run-back of the NPP power must be initiated, and in the latter load shedding. Load restoration must be done carefully to avoid underfrequency isolation. It is desirable that in the islanded section no generating unit should isolate earlier than the NPP.

If the grid has been operating under centralized AGC during the islanded mode of operation, this must be disconnected (see Section 2). The operation of the section in the islanded mode must be done in close co-ordination between the local load dispatcher and the operators of the NPP and other generating units. Operation of the islanded section in this manner will require efficient communication and information concerning the operating state. For grids of limited capacity with an NPP of comparatively large unit size, the islanding strategy should be properly planned. Various alternative schemes should be worked out and the best for the existing circumstances should be chosen. A typical case might arise when the generation of the NPP is shared between two grids through the tie lines; the NPP might be included in either when islanding takes place. From the NPP point of view it is better for the NPP to be included in the island, where after islanding the disturbances to it will be minimum; however, this might lead to a serious loss of generation in the other island, which might collapse as a result of a cascade tripping of generating units. Islanding schemes therefore should be worked out between the utilities concerned taking into account the operating characteristics of the NPPs. Survival of the NPP in the islanded section, where it may constitute a large fraction of generating capacity, is of the utmost importance, since tripping of the NPP would invariably lead to a grid collapse and the total loss of Class IV power supply to the NPP itself. During the islanded mode of operation, and despite optimum islanded conditions, random load fluctuations in the grid occur and the operational mode of the NPP might have to be changed to cope with the load fluctuation. This is discussed in later parts of this section.

Restricting underfrequency operation

In a grid of limited capacity, the lack of resources to provide extra power generation to meet peak demand and the inadequacy of measures to reduce the peak demand and bring about a flattened demand curve leave the utilities with two choices: scheduled power cuts to the consumer and underfrequency operation. Socio-economic constraints may force the utilities to resort to underfrequency operation.

All generating units including NPPs are capable of operating at nominal power at frequencies below the nominal frequency. NPP manufacturers usually guarantee operation at full nominal power in the frequency range of 49–50.5 Hz for 50 Hz systems provided that the voltage remains within 95–105% of the nominal value; an excitation control system for the generator can maintain such a voltage for frequencies within the frequency band. Provided that no restriction is imposed by the turbine, the NPP can be operated at full power down to a frequency of 49 Hz for a 50 Hz system (see Section 4.9).

However, during underfrequency operation the system will be more vulnerable to disturbances such as loss of generation due to tripping of the generating unit or tie lines. The frequency drop will depend upon:

- The loss of generation;
- The load reduction due to the drop in frequency;
- The amount of load shed.

The load reduction due to the drop in frequency depends upon the load mix in the grid and may vary from 1–3% per percentage point change in frequency. The initial frequency of operation, although it may be below the nominal frequency, should be at least high enough that the loss of the largest generating unit would not reduce it to a level at which isolation of any generating unit or tripping of tie lines would occur. If these do occur then cascade tripping of generating units and grid collapse are likely to follow. An analysis of frequency stability would help to assess the situation. In the event of loss of any other unit, the frequency might drop to a value at which the NPP might be forced to reduce its power or the operation of the turbine might become limited in time.

It should be noted that tripping of an NPP of large unit size operating in a grid of limited capacity would cause a severe frequency drop which could be averted by load shedding. The greater the frequency drop, the greater would be the amount of load shedding. The further the initial frequency below the nominal frequency, the greater would be the load shedding requirement. The limit of the underfrequency should therefore be properly worked out, taking into consideration the following factors:

- The size of the largest unit — probably the NPP;
- The grid stiffness;

- The power flow through the interconnection;
- The frequency for tripping the tie lines;
- The isolation frequencies for the generating units;
- The restriction in operation imposed by the frequency on the NPP and other generating units;
- The amount of load to be shed.

Tripping of a large generating unit such as an NPP will cause the grid frequency to drop rapidly. The rate of frequency drop will depend upon the following (see Sections 2.2 and 2.3):

- The load at the instant when the NPP trips;
- The amount of generation lost;
- The inertia of the system;
- The drop in the load due to the frequency drop;
- The stored energy available through the response of governors in the generating units.

At peak demand when a low performance grid is being operated at underfrequency, there is almost no stored energy available; the turbines are operated with load limiters close to the zero position. The rate of frequency drop could be very high in such cases: more than 1 Hz/s. Load shedding relays, which are provided with time delays of the order of seconds, would not be able to handle the situation, and major disturbances such as the loss of large generating units could lead to a grid collapse. The underfrequency of operation should therefore also take into account the capabilities of the load shedding scheme. If the frequency drop for the loss of the largest generating unit is 1.5 Hz or more and the rate of frequency drop is near to 1 Hz/s when the power system is operating at peak load, it would not be advisable to operate the grid at below 49.5 Hz for 50 Hz systems.

Load shedding

A major disturbance such as the loss of a large generating unit will cause the grid frequency to drop rapidly. Cascade tripping of generators caused by such a drop in frequency should be avoided by load shedding, particularly if the fall occurs very fast, since the spinning reserves take time to respond. Load shedding schemes involve the automatic disconnection of load in a gradated manner by underfrequency relays and sometimes by df/dt relays. The total amount of load shed, the set frequencies for initiating the load shedding and the amount of load shed at each frequency level, and the time delays incorporated with the operation of relays constitute the scheme. The scheme usually evolves from an analysis of frequency stability and depends upon the following factors:

- The size of the largest generating unit in the grid;
- The flow of power through the interconnection;
- The drop in frequency due to the loss of power through the interconnection;
- The drop in frequency due to the loss of the largest generating unit;
- The rate of frequency drop during the loss of maximum generation;
- The lowest frequency the grid is allowed to reach;
- The spinning reserve available through the response of the governor of the generating units;
- The initial frequency at which the grid was operating before the disturbance;
- The isolation frequencies of the generating units.

In a grid of limited capacity, underfrequency operation during the peak demand period is quite common. Furthermore, there is also no spinning reserve. Loss of an NPP of large unit size is likely to cause the grid frequency to drop very fast (see Section 2.3). The foregoing factors should therefore be taken into account when load shedding schemes are engineered so that sufficient load is shed to prevent the system frequency reaching a value which would cause a generating unit to isolate. This is because the tripping of any generating unit would add to the difficulties in the grid. The amount of load to be shed automatically would vary depending on the circumstances; however, provision must be made to shed automatically a total load equal to the generating unit of the largest unit size, perhaps the NPP. Load shedding should be implemented in stages at various levels of underfrequency in order to avoid undesirable disconnections of load and concomitant embarrassment and loss to the utilities. Two or three levels of load shedding are quite common. The time delay incorporated in the operation of underfrequency relays varies from zero to a few seconds. This is usually based on the requirement for load shedding to match the rate of drop of frequency and to allow for the possibility of spurious operation. The time to disconnect a load also includes the operational time of the breaker, which is usually 5 cycles (and therefore 100 ms for a 50 Hz system), and this should be taken into account in providing a fixed time delay for the underfrequency relays. A common measure to guard against the spurious operation of underfrequency relays is to provide a fixed delay of 20 cycles [12]. Sometime two out of the three arrangements are adopted in underfrequency relay operation in order to reduce the probability of spurious trips as well as to provide sufficient reliability in operation [12].

The use of df/dt relays may be resorted to in order to cope with situations involving high rates of drop of frequency. However, their use is not very common, and spurious operation due to small synchronizing oscillations has been reported. It would therefore be judicious to avoid situations which make the use of such relays essential. The choice of appropriate unit size of NPP (if this is the largest unit in the grid) and the implementation of a load shedding scheme with appropriate levels of underfrequencies are the best remedial measures.

In the islanded mode of operation the load shedding scheme must be properly envisaged taking into account the load changing capabilities of the NPP and the other generating units operating in the islanded section.

The proportion of the load subject to automatic load shedding varies from grid to grid, with 15–20% of the total connected load being common, though the figure can be as high as 50% for some high performance grids. Restoration of the active power balance by load shedding might create a serious imbalance of reactive power unless the shed load is appropriately distributed throughout the network. Grid collapse has been known to occur as a result of a serious imbalance of reactive power giving rise to severe voltage disturbances. The distribution of shed load must therefore be properly planned, and appliances such as synchronous condensers, reactors, etc., must be installed at sensitive points, including at the terminals of NPPs, to compensate for an imbalance in reactive power. However, it must be borne in mind that such reactive power compensators are expensive, and their sizing necessitates proper assessment of the requirements for reactive power balancing in many possible load flow situations.

It is interesting to note in this regard that in Finland large synchronous motors used for wood chopping are off-loaded to help restore reactive power balance. Off-loading synchronous motors and disconnecting loads of low power factor such as pump sets used for agriculture are two of the methods that can be used in a weak grid to maintain a balance in reactive power during the load shedding process. However, the distribution of the load shed involves socio-economic considerations, and a definite policy needs to be evolved in consultation between the utilities, the consumers and the government.

Load restoration

Load restoration is essentially a sequential process. It can be manual or automatic; when it is automatic, the same underfrequency relays used for sequential load shedding can be used for load restoration [12]. The load restoration scheme should be properly worked out with consideration for the priorities associated with different loads and the effect of load restoration patterns on the voltage and frequency conditions of the grid. Load restoration may involve switching off devices used for reactive power compensation. Automatic load restoration is not essential and if implemented it should be carefully arranged so that no upset condition arises in the grid as a result of this exercise. The load dispatcher should have all the relevant information about the power generation available, the load changing capability of the generating units, and the network conditions, including the status of the devices compensating reactive power, in order to implement load restoration in the proper sequence.

Implementation of an automatic generation control (AGC) scheme

In a low performance grid, underfrequency operation during peak demand is quite common. Moreover, the frequency varies over a wide range throughout the demand cycle in one day. This is due to the absence of automatic generation control. Wide frequency fluctuations are likely to cause transients in the NPP unless it is made insensitive to such frequency changes. Since these transients are deleterious to the life and performance of the NPP, the incorporation of AGC is essential for ensuring that the NPP performs properly. AGC involves automatically altering the power generated to match the load demand while maintaining the frequency within a narrow band (±100 mHz). AGC also controls the deployment of spinning reserves during a disturbed condition in the grid caused by loss of generation, as well as during the process of load restoration after load shedding. The AGC is worked out with the objective of maintaining the grid frequency within strict limits and utilizing the generating units in the optimum economic manner.

The capability of the AGC will depend upon the following:

- The cyclic generation capacity available in the system;
- The load changing capability of units;
- The load demand pattern;
- The magnitude of random load disturbances;
- The stored energy available in the generating units and the response of the governors to frequency changes.

The introduction of an NPP of fairly large unit size into a grid of limited capacity would therefore require a careful assessment of the foregoing for the development of a suitable AGC scheme so that the NPP could function as intended, e.g. as a base load station. Generally in a grid with a mixture of nuclear, thermal and hydro plants, NPPs are operated as base load stations, thermal stations provide the cycling capacity and the hydro stations perform frequency control. Where there are no hydro units the capabilities of the existing thermal units to perform grid frequency control should be examined before the introduction of the NPP. An existing AGC scheme is also likely to need to undergo modification following the introduction of an NPP.

Reactive power management

An NPP provides not only a large amount of active power but also much reactive power to the grid. Considerations concerning the radiation hazard to the population and other factors may dictate the location of the NPP far from the load centre. The transmission of reactive power over long distances is ridden with problems and needs to be tackled using local generation of reactive power. The introduction of an NPP would therefore require an appropriate scheme for reactive power management to ensure that the proper voltage is maintained at the NPP terminals and to maintain the desired voltage profile. This is usually achieved by way of load flow studies conducted for various operating conditions of the generating stations, loads and configurations of the network. Sufficient reactive power should be generated by the other units or the local compensating devices that the NPP generator can operate and transmit its full nominal power while remaining well within its stability limit. This may involve the operation of the rest of the generating units at a slightly lower power factor and the incorporation of reactors, capacitors and synchronous condensers of an appropriate size at suitable places determined in load flow studies, taking into consideration the operating characteristics of the NPP generator available from the NPP vendor.

The scheme for reactive power management should also take into account the absence of generating units, particularly the NPP, which may be largest, due to scheduled or forced outage. In the event of outage of an NPP, the shortfall in reactive power must be made up by other generating units and local compensators. It may therefore become necessary to provide a local compensating device for reactive power at the NPP terminal to maintain suitable voltage conditions for running the auxiliaries and for startup.

NPP generators provided with fast-acting excitation control systems consisting of thyristor devices and connected with the rest of the system through long tie lines may become subject to power frequency oscillations. It has been found that a power system stabilizer incorporated in the excitation control circuits helps to reduce the magnitude of such oscillations.

Power system stabilizers are used in the Nordel (the power system of the Nordic countries, consisting of Sweden, Norway, Denmark and Finland) grid. However, these stabilizers are also known to cause stability problems when badly matched with the system, and the need for them and their effectiveness should be properly evaluated before putting them to actual use.

Transmission lines

Suitable transmission lines should be installed to transmit the active and reactive power from the NPP generator. They should be sized for both economic transmitting capacity and surge impedance loading. Sufficient redundancy in capacity and/or in number must be provided to withstand the outage of transmission lines. Provision for suitable on-line switching is also required. Potential radiation hazards may dictate the location of the NPP far from the load centre. The cost of the long distance transmission of active and reactive power in such a case would add to the cost of the power system network. It is therefore worth while giving due importance to the distance between the proposed NPP location and the load centre in the planning stage.

Provision might need to be made for a separate grid supply of lower voltage from a neighbouring area to supply power to the auxiliaries and for startup. For a weak grid, this may often turn out to be a viable solution for providing a reliable grid supply for the residual heat removal (RHR) system of the NPP as well as for startup. The short-circuit level of such alternative supply lines should be verified for proper functioning of the auxiliaries and to avoid their tripping owing to undervoltage.

Protection

The network protection system must ensure the prevention of outage and or damage to the NPP due to system faults, including three-phase short-circuit faults very close to the NPP, which are the severest. The effects of such faults have been discussed in Section 2. The duration of the three-phase short circuit that the NPP can tolerate without tripping or sustaining damage depends upon the individual design. However, in order to avoid excessive torsional stress on the turbogenerator shaft, manufacturers usually recommend a fault clearing time of 150 ms as an upper limit. Protective relays in the network together with circuit breakers of suitable speed must ensure the clearing of such faults.

In the event that such a performance by the network system is not guaranteed, as may be the case for grids having a limited capability for protection, an effective alternative method is to disconnect the generator, and thus the turbogenerator of the NPP, from the grid. Immediate resynchronization may be possible in this case, if required. This can be achieved by the use of power plant disconnect relays [13] that operate on the basis of a drop in the active power, which usually happens during a short-circuit fault. Such relays ensure disconnection within 220 ms, comprising the permissible time of 150 ms for fault clearing by the network protection system and 70 ms operating time for the circuit breaker of the generator. The disconnect relay of the power plant ensures isolation of the generator if the fault lasts longer than 150 ms.

‘Autoreclosure’

‘Autoreclosing’ of lines after the clearance of transient faults increases the line availability and the avenue for the dispatch of power and as such is a welcome feature. However, this induces extra stress on the shafts of the turbogenerators. It may induce problems related to the stability of the power system, particularly when the network is small. Wherever series capacitors are fitted in the transmission lines, subsynchronous torsional oscillations, which may seriously endanger the turbogenerators, are expected to occur on autoreclosure.[7] The autoreclosing feature is

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[7] This derives from experience in the United States of America.

not universally adopted in high performance grids. In the Federal Republic of Germany, autoreclosing is permitted only for single-line-to-ground faults while in the Nordel grid it is not permitted for large stations or for NPPs. The risks incurred in incorporating such a feature should therefore be carefully evaluated before implementation.

System restoration after grid collapse

A definite strategy should be worked out for restoring the system in the event of a collapse of an islanded section containing an NPP or of the total grid, the former being the more frequent in a weak grid. The restoration procedure must take into account the special needs and characteristics of NPPs and ensure an off-site supply of suitable quality to the NPP as early as possible. The source of off-site power and the supply route should be decided upon and redundancy should be incorporated.

Information and communication (see Section 2.6)

Communication should be established between all generating stations and load dispatch centres, particularly between the NPP, the load dispatch centre and neighbouring stations. Relevant data about the NPP and neighbouring generating units and the related network should be made available to the load dispatcher to assist in achieving the optimal performance of the NPP and its survival under disturbed conditions of the grid. Such assistance might include prior warning of a decision to island the NPP and the mode of islanding so that the NPP operators could take anticipatory action, as well as arranging suitable off-site power for running the auxiliaries of the NPP for startup.

Power system management (see Section 2.7)

The degree of success that can be expected in the use of an NPP of large unit size depends very much on the management which controls the operation of the power system. Management includes the planning and execution of measures in the grid for the incorporation of the NPP and of strategies for normal and contingent operations. The management should include all the relevant authorities taking part in the operation of the interconnected system. The task of management becomes more complex because of constraints inherent in grids of limited capacity. Such grids need stricter control and the continual review of performance and operating strategies as operational experience accrues. An understanding on the part of the managers of power systems of the special needs and characteristics of NPPs and the factors determining their economic viability is essential for successful integration of an NPP into a grid of limited capacity.

5.1.6.2. Investigation of modification of NPP characteristics

While it is advisable to introduce all the measures necessary in the grid to create an environment suitable for the operation of NPPs of standardized unit sizes as per design, the cost involved and the limitations on the existing infrastructure may prevent the full achievement of the target. The grid characteristics will therefore be inferior to those of grids in which the NPPs have been successfully operated. It is judicious therefore also to investigate what modifications are possible to the characteristics of the NPP and at what cost to enable the NPP to be operated reasonably successfully in such a grid environment.

It is quite likely that only minor changes and marginal modification to the operating characteristics of the NPP would be possible at a reasonable cost. Major changes in equipment might be expensive and might result in an unproven plant. The feasibility of modifications and the cost inolved should be evaluated in consultation with the vendors of the NPP. Most of the major changes needed must therefore be made to the grid. Deficiencies in the grid characteristics impose an economic penalty on the performance of the NPP. It is left to the utilities concerned how to strike a balance without affecting the safety of the NPP. A cost–benefit analysis might help to determine cost effective measures. Guidelines for such an analysis are given later (see Section 5.3). Deficiencies in the grid performance characteristics that would affect the performance of the NPP and require its modification can be broadly stated as follows (see Section 2):

- A shortage of reactive power;
- A shortage of power generation to meet peak demand, resulting in underfrequency operation;
- A frequency variation beyond the dead band of the governors;
- A voltage variation, particularly on the below-nominal side, of well over 5%;
- Islanding that might be more frequent than desirable;
- A still high probability of loss of off-site power;
- A network protection system that may not be adequate.

Shortage of reactive power

Studies of the load flow that took into consideration the power to be transmitted from the NPP, the location of the NPP and the transmission line characteristics would help in assessing the requirements for reactive power. It is quite probable that under different grid conditions the NPP generator would need to operate in both an overexcited and an underexcited state, with lagging and leading MVAR respectively. The maximum requirement for reactive power in both cases, as well as the load angles of operation, must be checked with the characteristics of the NPP generator supplied by the vendor. The reactive power requirement of the grid might necessitate operation of the NPP generator at a slightly lower power factor than that specified by the manufacturer. Such a situation would require either a generator with a slightly higher megavolt-ampere rating or operation of the generator at a slightly reduced power. The difficulty is compounded by underfrequency operation. Similarly, a grid demand for operation of the NPP generator at a higher leading reactive capacity than that permissible on the basis of the generator characteristics would call for reduction of the level of the operating power to keep the operation of the generator within the limit for steady state stability. It would be advisable for the prospective owner to discuss the requirement of the NPP generator for reactive power with the NPP vendor and to explore the possibility of obtaining at a reasonable cost a generator with characteristics close to those desired. However, it is unlikely that the generator units associated with standardized NPPs would be amenable to any change, and the problem of reactive power management must be tackled at the grid end through the help of local reactive power compensators.

Underfrequency operation

Underfrequency operation during peak demand is quite common in weak grids. Most standardized NPPs guarantee operation at full nominal power in the frequency band 49–50.5 Hz for 50 Hz systems provided that the voltage remains within the 95–105% range. In weak grids during an acute shortage of power the operating frequency may dip below 49 Hz and approach 48 Hz. Underfrequency is normally accompanied by undervoltage owing to a shortage of reactive power; the voltage may fall to 90% of the nominal value. It would be desirable for the grid to have an NPP which could generate full nominal power continuously for a period of 12 hours (the peak demand duration) at 48 Hz and 90% of nominal voltage with no adverse effects on the NPP components, especially the turbogenerator. The prospective owner of an NPP should find out from the vendors whether the desired performance could be obtained from the standardized units with possible modifications.

The limitations in underfrequency operation arise from the generator, when coupled with an undervoltage, from the turbine and from a reduction in the primary coolant flow, particularly for PWRs and CANDU PHWRs. It might be quite possible to obtain a turbogenerator that would meet the requirements. A slight overcapacity might be needed to overcome the limitation imposed by the primary pump. One of the factors in choosing an NPP is therefore the maximum power that the NPP can generate during such underfrequency and undervoltage conditions. Most NPPs are capable of being operated at 90% of nominal power under these conditions provided that the turbine has been designed for such operation. The prospective NPP owner has to weigh the cost of modifying the NPP against the gain in the operating power level. However, the vulnerability associated with operating the grid at such an underfrequency should also be given due weight.

Frequency variation

The frequency in a weak grid without AGC can vary over a wide band, exceeding ±1%. The transient caused by such a frequency variation has already been discussed in Section 4.4. NPPs intended for use as base load stations must be made immune from these transients. This is particularly applicable for PWRs which are operated in the reactor-follow-turbine mode. Such transients would call for changes in reactor power and the movement of control rods, which would be subject to fatigue and would need additional maintenance and surveillance. The turbine throttle valve would therefore need to be made insensitive to grid frequency variations within a certain band: say 49–51 Hz. In BWRs the throttle valve is insensitive to variations in grid frequency and hence does not require any special provision. The choice of the band must be made jointly by the operating staff of the NPP and of the grid. Particular care must be taken in choosing the upper limit of the frequency, and it must be ensured that the turbine does not trip as a result of overspeeding when full load rejection occurs at the highest operating frequency. This is of particular concern with some PWRs where a turbine trip at full power results in the tripping of the NPP.

The operating band of the turbine load limiter should also be made as narrow as possible to minimize the effect of the variation in grid frequency on the NPP.

Voltage variation

In a low performance grid, variations in voltage exceeding ±5% are common. High voltages might be expected at the terminals of the NPP only when it is not operating, and particularly when the NPP is connected with the rest of the system through long transmission lines. Voltage variations affect the operation of the auxiliaries. The prospective NPP owner should discuss the following with the NPP vendor:

- The limits to the operating voltage for the auxiliaries;
- The voltage drop in the transformers with a full auxiliary load;
- The voltage drop in lines and cables;
- The minimum startup voltage for the auxiliaries;
- The capability of the generator to regulate the voltage;
- The facility for tap changing, on load and off load, the percentage of taps provided on the transformer, and the reliability of the tap-changing gear;
- Protection for motors and their settings against undervoltages;
- Protection against overvoltages, if any, and its setting.

The excitation system of the generator can control the voltage to within ±5%, and the transformers, particularly unit auxiliary transformers and startup transformers, are provided with ~10% taps. A slight increase in the tap setting, by 2%

or so, may be enough to maintain the requisite voltage at the auxiliary supply terminals.

To guard against occasional high voltage conditions, protection against overvoltage may be provided; however, if the occurrence of a high voltage after outage of the NPP is a regular phenomenon, devices such as reactors to compensate for reactive power might need to be installed to supply the right voltage to the auxiliaries for starting the NPP. However, such reactors are expensive. If a separate startup transformer supplied from a separate grid supply is planned, the provision of suitable taps with a load tap-changing facility might be economically more viable than the provision of reactors at the terminals of the NPP. To guard against unreliability of the tap-changing gear, the possibility of choosing auxiliary motors with a lower nominal voltage might be investigated. However, protection against overvoltages becomes obligatory in this case.

Inadequacy of the network protection system

If the network protection system is inadequate to clear the fault within 150 ms, or if the reliability of its performance is questionable, a means of isolating the NPP from the grid should be provided as a backup protection for the NPP. This can be achieved by relays to disconnect the power plant [13]. An automatic transfer to house load when the voltage falls to a certain value can also serve as backup protection in case of an unsuccessful fault clearance. Some PWR manufacturers provide for automatic house loading if the voltage falls below 70% of the nominal value, thus averting tripping of the NPP due to undervoltage tripping of the auxiliary motors. Some PWRs are also tripped by a high rate of frequency drop, a typical value being 5 Hz/s for a 60 Hz system[8].

Operation in the islanded mode

Islanding usually starts with excess power generation in the grid because the load to absorb the generation of the NPP is lost. The NPP must thus withstand the load fluctuation in the islanded condition with an initial imbalance between the generation and the load. Large fluctuations in voltage and frequency are likely to occur in the islanded section, with the onus of control of the frequency and voltage being on the NPP, since it commands most of the active and reactive power in the island. An islanding scheme should be worked out so that the NPP can operate almost at its original power level and there are enough generating units with sufficient load changing capability to cope with the load fluctuation. However, this may not happen in practice, and the NPP may find itself in an island where the voltage and frequency

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[8] Communication from Bechtel Power Corporation, United States of America.

vary widely. NPPs designed to operate as base load stations are likely to experience difficulties unless they are capable of load following to a certain extent and a suitable control scheme and operating strategy are devised to enable them to follow load. It has been observed that most of the outages of NPPs in weak grids occur because of inappropriate islanding schemes and the inability of the NPPs to endure in the islanded mode of operation. For a weak grid, where islanding is likely to occur frequently, NPPs must have some load following capability even though during normal operation they serve as base load stations. The voltage in the islanded section must be controlled by the grid since the capability of the NPP generator is limited. However, the NPP must be capable of participating to a large extent in frequency control of the island. Operation in this mode would involve the following:

- A quick run-back of power to a suitable level to reduce the excess power generation and avoid a severe frequency rise;
- Transferring the turbine control to speed governor control;
- Changing the control scheme to reactor-follow-turbine mode.

The power level to which the NPP should be run back depends on the following:

- The upper limiting frequency of operation of the NPP. If the frequency can be reduced by governor action alone, the NPP can be operated at a higher power level while bypassing steam into the condenser. There is no need to match the NPP power with the load under these circumstances. This mode of operation is usually adopted in house load operation.
- The effect of the power level on the capability of changing load. The decision on the power level to which the NPP is run back must take this effect into account so as to remain able to meet a sudden increase in the load demand.
- The ease with which the NPP can match the fluctuation in load, particularly a load increase, within its load change capability.

Operation in the islanded mode therefore consists of a combination of steam dumping and the reactor-follow-turbine mode of reactor power control. PWRs which are intrinsically load following and operate in the reactor-follow-turbine control mode are inherently adaptable to the islanded mode of operation. However, during such an operation the control rods are subjected to substantial movement in either direction. Frequent cyclic movement of control rods could cause fatigue. For BWRs and CANDU PHWRs which operate in the turbine-follow-reactor mode of control, the control mode needs to be changed. For BWRs it would be advantageous if the power level were kept above 60%, so that power control could be effected by way of recirculation flow control and a higher rate of load change would be possible. The task of the control system in a BWR would therefore be to maintain the reactor pressure constant by bypassing steam into the condenser and to control the recirculation flow while the turbine throttle valve is left to respond to the speed governor.

For a CANDU PHWR, which can operate in either the turbine-follow-reactor or the reactor-follow-turbine mode, the power level should not be reduced below the poison-out level, which is around 65% with the NPP operating at full nominal power before islanding. During operation in the islanded mode, the turbine and the process system (the transport systems for steam and primary heat) have to bear the entire brunt of transients. However, changes of reactor power and movements of control rods should be reduced, particularly for LWRs. While excess power can be relieved by dumping steam into the condenser, increases in power are limited by many factors, described in Section 4.12. It is advisable therefore to maintain the power of the NPP at the highest possible value and to relieve excess energy by steam dumping.

The limit to power run-back and the changeover to a suitable control strategy can be evolved through simulation studies. Realistic data might be limited and the initial conditions might vary considerably; nevertheless, fairly representative pictures can be obtained. A model of the islanded section should include the network, a simplified representation of other generating units and a detailed model of the NPP for the representation of its dynamic behaviour. Since the network is likely to be small and the number of generating units to be few, and the duration of studies is not likely to exceed 15 minutes, such computer simulation studies need not be very expensive. During islanded operation it is essential that the NPP be under automatic control. However, participation of the NPP operator to a large extent would also be required, because of the possible inadequacy of the control scheme in meeting the variants encountered. Control schemes also need to be modified as operational experience accumulates.

For the effective participation of the NPP operator in the islanded mode of operation, relevant information about the grid should be available in the NPP control room. The display of electrical parameters in the control room of the NPP assumes much more importance for weak grids where disturbances are expected to be more frequent.

Operation in islanded mode must be performed in close co-ordination between the local/regional load dispatch unit and the operating staff of the NPP and other generating units, with the operator of the NPP taking the lead, since the NPP may provide the bulk of the generation in the island and the survival of the island depends upon the survival of the NPP.

NPP operators should therefore be trained to handle the situation arising from islanding. Such training can be imparted through training simulators. However, training simulators available commercially do not include a model of the grid in sufficient detail to represent realistically operation in islanded mode. Increasing the scope of the training simulator to include a model of the grid in the necessary detail is likely to be very expensive. As a minimum measure, the NPP operators should be made familiar with the off-line simulation studies related to operation in islanded mode, so that they become familiar with the dynamics of interaction between the NPP and the grid under such disturbed situations.

When sustaining the NPP in islanded operating mode becomes no longer possible, house loading of the NPP has to be performed. The decision to house load must lie with the NPP operator and preferably should be executed in consultation with the regional/local load dispatcher, since house loading of the NPP may lead to the collapse of the grid. In some NPPs, there is provision for automatic house loading, depending upon the grid frequency and grid voltage. Discussions should be held with the NPP vendor to ascertain the effect on the NPP of relaxing these limits, and the modifications required, and the cost entailed, if such relaxation is desired.

With regard to the survival of the NPP, the NPP operator should be authorized to initiate house loading in anticipation before the limiting conditions in the grid are reached and house loading takes place automatically. Wherever such action is not automatic, the possibility of implementing an automatic system should be investigated or else the decision to house load will depend entirely upon the judgement of the operator. The decision to house load should be exercised with caution, since house loading the NPP may lead to grid collapse and the house loading operation itself may not be successful, leading to NPP grip and total loss of Class IV supply.

High probability of loss of off-site power

The link between the probability of loss of off-site power and the reliability of the reactor protective system (RPS) has already been discussed in Section 4.14. The higher availability requirement of the reactor protective system arising from the higher frequency of loss of off-site power can be ensured by increasing the test frequency and reducing the duration of the test for the reactor protective system. In designs where the RPS uses semiconductor logic and automatic self-testing through electric pulse circuitry or by computer is provided, no special effort will be necessary. However, in designs where such automatic testing is not provided, the frequency of tests has to be increased. On-site power supplies are designed with a certain target reliability based on a certain rate of failure of the off-site power supply system (see Section 4.15). Ways and means of increasing the reliability as required because of the poor reliability of the off-site power supply should be discussed with the NPP vendor. One may consider providing more diesel generators so as to increase redundancy or increasing the capacity of individual units. The cost implications must also be taken into account.

Effect of grid-induced transients and trips

An NPP operating in a grid of limited capacity is likely to be subjected to more trips and other severe transients, besides smaller transients occurring frequently. The effect of these transients on the life of components of the NPP should be discussed with the equipment suppliers. The need for instrumentation for surveillance in crucial areas should also be discussed with the NPP vendor and if possible the necessary equipment provided. Any increase in the scope of in-service inspection and additional maintenance that might be needed should be planned in consultation with the vendor. The use of instrumentation employing noise measurement techniques may be considered for surveillance purposes.

Operation of the turbogenerator after a reactor trip

When the NPP trips, the stored energy in the NPP can be used for a few seconds to provide power to the grid. After the NPP trips, the generator is left connected with the grid and is automatically disconnected by the reserve power relay. A delay can also be provided between the reactor trip and closure of the turbine stop valve. The length of the delay is dependent upon the cooldown of the primary coolant system and the permissible fall in reactor pressure. For a grid of small capacity this NPP feature is advantageous since it compensates to some extent for the time delay involved in the response of the spinning reserve. Turbogenerators in CANDU PHWRs are provided with sufficient cooling, and motoring of the turbogenerator is permitted for a limited time, to facilitate the quick take-up of power (Appendix V).

5.2. COMMISSIONING TESTS

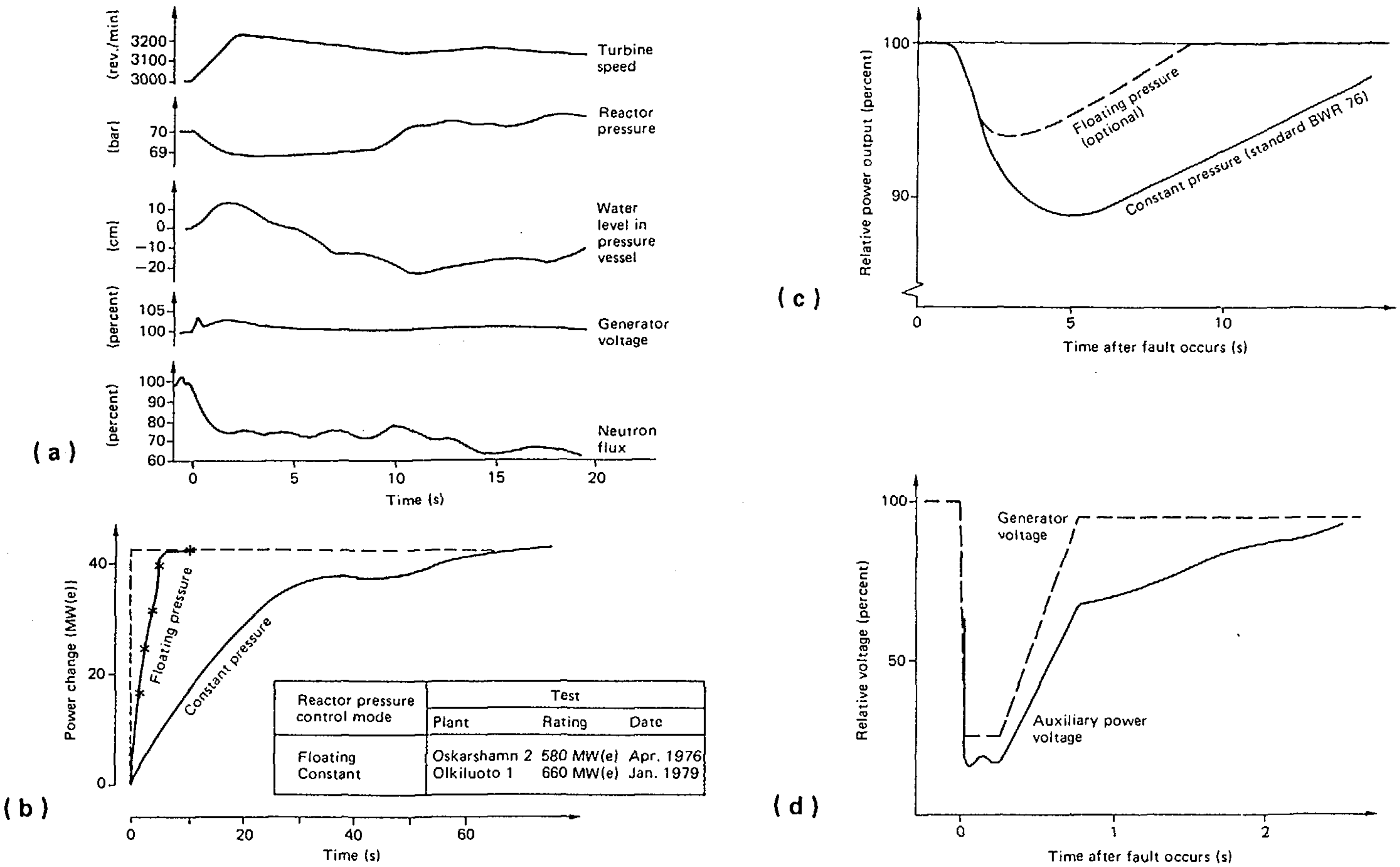
It is advisable for the NPP owner to conduct tests on the NPP during commissioning so that the performance of the NPP may be satisfactorily demonstrated.

Commissioning tests should include:

- load rejection test with the NPP operating at full nominal power and operation of the NPP under house load for at least one hour
- turbine trip test at nominal full power of the NPP
- step load change capability and ramp load change capability
- power run-back capability test
- short circuit at the NPP terminals, particularly for BWRs.

Results of some of the tests cited above are shown in Fig. 9 a–d.

The NPP owner should preferably request the supplier of the NPP for results of simulation studies regarding the above. Experimental tests will help to validate the results of simulation studies and lead to modifications and updating of the models used in simulation studies. It will be immensely helpful if signature patterns of the important variables are monitored, e.g. neutron power, primary coolant pressure, steam generator pressure, water level in the steam generator/reactor, steam flow through turbine bypass valves, turbine speed, movement of turbine throttle and interceptor and bypass valves, generator voltage, etc.



Reactor pressure control mode	Test		
	Plant	Rating	Date
Floating	Oskarshamn 2	580 MW(e)	Apr. 1976
Constant	Olkiluoto 1	660 MW(e)	Jan. 1979

FIG. 9. NPP test results. (a) Load rejection at the Barsebeck NPP (100% = 580 MW(e)); (b) Step change tests. (Courtesy of ASEA-ATOM, Sweden.); (c) Effect of a short circuit in the grid near the NPP on electric power output; (d) Effect of the same on generator voltage and motor terminal voltage.

It will be of considerable help if important variables during transients caused by major disturbances such as net load rejection are recorded. In a weak grid, house loading of the NPP might have to be resorted to rather frequently and success may not be achieved all the time because of improper working of the instrumentation and control system components. It is necessary therefore to diagnose the cause of failure and attend to the deficiencies. It is desirable therefore that the NPP be equipped with a device for transient recording which is triggered automatically when major disturbances such as load rejection, turbine trip, etc., occur. Commissioning tests should also include automatic transfer of the supply to auxiliaries from grid to generator and vice versa and automatic transfer of the supply from the main grid to a separate grid. The automatic startup of diesel generators initiated by detection of loss of grid voltage should also be tested. The performance and startup of auxiliaries for undervoltage conditions should also be tested to the extent possible by adjusting the taps on the transformers.

5.3. COST–BENEFIT CONSIDERATIONS

To keep the safety risks due to a high probability of loss of power within the stipulated criteria laid down by the licensing authorities, and to keep the loss of availability of the NPP due to grid disturbances within acceptable limits, certain measures, including the installation of additional equipment, have to be introduced in the grid and wherever possible in the NPP. Such measures may require a considerable investment depending upon the existing characteristics of both grid and NPP and desired improvements. The required investment needs careful assessment.

Investments necessary to improve the characteristics of a weak grid up to a level which would permit high availability of the NPP may be beyond the utility's financial capability. In this case the utility concerned must decide how to compromise between investment costs and a loss of performance by the NPP and the grid as a whole. However, the investment required to improve the reliability of both off-site and on-site power supply systems so that the probability of total loss of power (station blackout) is kept within the criteria laid down by the licensing authorities becomes obligatory if the NPP has to be introduced within the grid. Any relaxation in this respect has to be cleared by the licensing authority concerned. The reliability of off-site power can be assessed by means of analytical techniques which are fairly well established. However, such analytical methods are quite complex and their results are very much dependent on the data on the failure probability of various components. It is very difficult to collect and generate data which are realistic and results of the analyses are likely to be unreliable.

It is advisable therefore to depend upon the overall failure data accumulated through experience in operating the actual power system. For evaluation of the reliability of the on-site power supply, one essentially has to depend upon information supplied by the vendor. However, it is recommended that these data be cross-checked wherever possible with the data gathered in the operation of similar plants.

Various methods for improving the reliability of off-site and on-site power supply systems have been described in Sections 5.1.6.1 and 5.1.6.2. The best measures to take depend on the specific situations, and have to be evolved by the utilities concerned. However, the most cost effective measure for improving the reliability of the off-site supply appears to be the provision of an alternate grid supply using separate transmission lines. Improvements in the reliability of the on-site power supply system can be achieved by better maintenance and more frequent periodic testing.

The adverse effect of grid disturbances on the performance on the NPP is reflected directly in the number of grid-induced outages. It is rather difficult to predict the frequency of such events. However, a study of the available data regarding abnormal frequency and voltage conditions in the grid along with related operating characteristics of the NPP may permit a good guess as to the frequency of events leading to islanding or house loading of the NPP. It is reasonable to assume that 50% of such events will lead to a trip of the NPP (Appendix IV).

For each trip it will be quite conservative to assume a downtime of 24 hours for LWRs and 42 hours (including poison-out time of 36 hours) for CANDU PHWRs. This is a realistic estimate for the loss of availability of an NPP due to grid disturbance. However, the impact of grid disturbances is not restricted to the outage of the NPP. The possible adverse effects these can have on the life of NPP components and concomitant requirements for increased surveillance and maintenance have already been discussed (see Section 4.13). The indirect cost associated with a forced NPP outage, i.e. loss of revenue and goodwill associated with frequent load shedding, has also to be reckoned with.

In this connection it may be noted that in a weak grid, small multiple units will be preferable to a single large unit as regards overall economic performance on the whole power system although as regards capital cost, multiple units are at a disadvantage compared with a single unit of equivalent capacity.

Although it is always worth while introducing measures not requiring large investment in the grid, to improve its performance, i.e. protection, control, instrumentation and communication measures, other measures requiring large investment, such as the installation of transmission lines of considerable length, a large number of reactive power compensators, or the creation of spinning reserves, merit careful evaluation and should be implemented only after acquiring experience in operating the NPP in the actual grid environment.

6. REMEDIAL MEASURES BASED ON NPP OPERATIONAL EXPERIENCE

It has already been observed that it is always advantageous to incorporate the desired modifications into the NPP as well as into the grid in advance so as to avoid retrofitting, which may be expensive. This is particularly true for NPPs where retrofitting may not only be expensive but sometimes may not be possible at all. Such cases may include provision for dumping steam into the condenser or increasing the dumping capacity, which may not be possible owing to restrictions in the layout of an NPP already installed, where major changes involving considerable expenditure would be entailed. Similarly, improvements in the generator, turbine, or load change capability of the NPP may not be possible. However, it is clear from operating experience that some modifications in the NPP are possible.

- Provision of suitable on-load tap-changing gear on auxiliary transformers or changing the percentage of taps. Even without recourse to provision of on-load tap-changing gear, based upon operating experience, a suitable tap on the transformers can be chosen to cater for an undervoltage situation. Overvoltage protection needs to be provided in this case.
- Provision of a reactive power compensating device at the NPP terminal or a separate transformer with or without on-load tap-changing gear to be supplied by a separate grid of lower voltage.
- Alteration of the settings of undervoltage and underpower relays for auxiliary motor protection. It may be worth while eliminating underpower relays.
- Alteration of the station isolation frequency; a higher value may be desirable to guard against other generating units isolating earlier.
- Incorporation of a power plant disconnect relay or of an automatic house loading scheme through undervoltage sensing.
- Modification of the NPP power control system to enable load following operation within permissible limits, particularly in the islanded mode of operation.
- Modification of the turbine oil system, making the throttle valve insensitive to grid frequency change and changing the setting of the load limiter.
- Incorporation of a self-checking feature in the reactor protective system. This is possible only when the logic employed uses semiconductors.
- Improvements in the on-site power supply system. These include provision of additional diesel generators depending on data regarding failure to start and frequency of maintenance; augmentation of the battery capacity.
- Provision of instrumentation for surveillance in critical areas recommended by the NPP manufacturers.
- Instrumentation for sensing and recording the major plant variables during selected transients.
- Provision of anticipatory signals such as loss-of-load to open dump valves.

Plant operating limits, operating procedures and routine testing procedures are also likely to undergo modifications, depending upon operating experience. Every grid-induced outage should be analysed, preferably with the aid of recordings of transients, to trace the sequence of events and ascertain the reasons for the outage. Suitable modifications to hardware and software, e.g. changes of settings, operating procedures etc., may be incorporated within the existing constraints.

While the NPP characteristics remain fairly fixed, the grid characteristics are likely to change during the operating life of the NPP. It is therefore worth while incorporating the desired changes in the grid wherever possible rather than attempting to make major changes in the NPP. Many of the desired modifications can be incorporated in the grid even after the NPP is installed. However, the utilities have to bear with the economic penalties imposed on the performance of the NPP by the deficiencies in the grid characteristics, till such deficiencies are countered by appropriate measures.

7. EXPANDING THE SHARE OF NUCLEAR CAPACITY IN THE GENERATING MIX

The trend towards increasing dependence on nuclear power for the commercial generation of electricity is evident in a number of industrially developed countries. Successful integration of NPPs of large unit sizes up to 1300 MW(e) has been accompanied by the necessary evolution of the power system needed to accommodate such NPPs. Progressive changes in the nuclear component also call for corresponding changes in the power system. It is therefore necessary for those countries committed to a long-term nuclear power programme to take into account the changes called for in the power system when planning expansion of the grid.

The scope of such planning activity has already been described in Section 5. The special considerations needed to accommodate NPPs in increased number are discussed in this section.

It has already been pointed out that a highly interconnected system is conducive to the efficient operation of large units; the generation mix — thermal, nuclear, hydro — available in the interconnected systems can be effectively utilized so that the generating units operate in the economically optimum manner. The possibility of transmitting a large amount of power over a long distance using high voltage DC transmission has also made the task of interconnecting far-away regions easier. It is worth while therefore to plan the expansion on the basis of integrated system operation so as to determine the quantum of nuclear power generation that could be successfully accommodated. The expansion will involve the evolution of specifications for the new generating units, especially thermal and nuclear. The specifications must consider their dynamic characteristics under varying grid voltage and frequency. The Nordic countries [14] and the Federal Republic of Germany [15] have evolved specifications appropriate to their current power systems' quality and reliability levels.

For an NPP such specifications typically include the following:

- PWR nuclear power units should be designed for a power response rate of at least 5% full power per minute within the output range of 60–100% full power. At outputs below 60%, the power response rate may be limited to the maximum power response rate permissible for the turbine.
- BWR nuclear power units should be designed for a power response rate of at least 10% of the operating power level per minute. This rate of change should be possible over a range of at least 30% of the operating power level. In this range the power can be controlled by varying the speed of the main circulation pumps. Over the remainder of the power range between minimum load and full load, the power response rate shall be at least 10% of full power per minute.
- Nuclear condensing units should be designed so that they can be used for daily and weekly load following during certain periods of the year, using the rates of load change specified above.
- The units should also be designed in such a manner that, if necessary, they can participate in following the occasionally varying loads which cause frequency variations in the interconnected power system. This implies that the units should be capable of accommodating power changes without intervals by ±2% of full output within a 30 seconds period. The units should be capable of performing these changes within the ranges specified above.

The above specifications relate to the normal operating state. Specifications regarding power response capability during power system disturbances include the following:

- PWR nuclear power units in which the power change signal is applied directly to adjust the turbine control valve should be designed in such a manner that a power step of 10% of full power can be accommodated within 30% of the power range. BWR nuclear power units operating on pressure control should be designed in such a manner that within the range of pump control they shall be capable of accommodating a power change of 10% of the initial value within 30 seconds.
- After the power changes specified above, nuclear power units shall also be capable of accommodating a load change at the rate applicable to the normal operating state.
- Nuclear units should be designed in such a way that they can be used as spinning reserves and then deal with the above mentioned power variations, if serious disturbances occur in the grid.
- In the event of very serious (and exceptional) disturbances, where the power system is divided into smaller grids, the units should also initially be capable

of making the above mentioned power changes (upwards or downwards) and then achieving stable operation and normal power control capability.

The specifications have been drawn up with a view to producing standardized NPPs which can perform all the tasks faced by generating units in a power system, especially load following and frequency control. The capabilities of the currently available NPP units as regards accommodation of load change requirements in connection with scheduled load following and network frequency control are very close to the desired specifications. In fact, the load change capability of NPPs is better than that of coal-fired stations, which is around 4% per minute, and in certain ranges better than that of oil-fired stations, which is around 8% per minute. CANDU PHWRs have very large load changing capability, up to 60% per minute. However, it is restricted above the poison-out power level (65%). The turbine loading rate may also restrict this capability. However, the load change capability of the NPP depends upon many factors, particularly the xenon level, reactivity reserve and neutron flux distribution change caused by movements of the control rods. Even allowing for such conditional restraints, the load change capability of NPPs can satisfy the requirements in connection with the scheduled load following and frequency control duties expected in a high performance grid.

The decision to subject the NPP to load follow and frequency control operation rests on the economic viability of the NPP compared to that of thermal stations which normally provide the cyclic generation capacity in a grid and on guaranteeing performance of the NPP during cyclic load changes without any adverse effect on the components. Components that are affected by such cyclic loading are fuel, control rods, the control rod drive mechanism, guide tubes, and mechanical structures of the reactor coolant pressure boundary. In-plant test programmes and modifications in different areas, especially that of control rod devices, have been carried out to prove NPP performance under load cycling [16].

Load regulation and frequency control induce significant loading on reactor components, particularly mechanical fatigue and wear of control rods due to frequent insertion and withdrawal (approximately 2×10^5 steps per year). Tests have been conducted to perform mechanical qualification and verify endurance in a full-scale set-up with drive mechanisms, guide tubes and a fuel assembly. Four control rods, including two with improved design features, were tested in some instances for up to eight million steps.

These tests revealed appreciable wear of the control rod tubes due to mechanical rubbing against the guide tubes, necessitating changes in the hydraulic design of the guide tubes.

Wear of the drive mechanism latch arms controlling travel and locking of the drive shaft has been observed, calling for design changes.

As a result of the effect of cyclic load change on primary coolant mechanical structures, design changes to minimize loadings (especially thermal stresses) at sensitive points became necessary. These changes were based on feedback from operating experience. An example of such a change is the pressurizer control system design alternatives introduced to minimize thermal stresses on the charging line nozzle of the chemical and volume control system [16]. Control rods in CANDU PHWRs are located in the moderator region, which is at a much lower pressure and temperature than the control rods of LWRs. This environmental condition, coupled with simple design and construction, makes the effect of load cycling on the control rods of a CANDU PHWR much less severe than it is in LWRs (Appendix V).

Load regulation and frequency control involve significant local power variations caused by control rod movements, particularly in PWRs. The reactor protection system therefore has to be engineered to monitor continuously the local power and the margins with respect to various core limits (DNB, linear power density, etc.). This needs a sophisticated computer-based system performing on-line calculations based on input data such as primary coolant temperature and pressure, coolant flow rate, power level and power distribution.

To optimize fuel burnup and the power distribution during scheduled load follow operation of a PWR, a sophisticated control system using a computer may also be necessary. In some PWRs this is done with the help of a real-time core simulator.

For BWRs, since the power change is effected mostly through recirculation flow adjustment, such a sophisticated control and protective system may not be necessary. However, after attaining the power level the control rods are moved to readjust the recirculation flow to the desired level. Close monitoring of the power distribution is therefore necessary.

Although by design the NPPs are capable of effective participation in load following and frequency control activities, sufficient operating experience to guarantee performance has not yet been accumulated. Licensing authorities may demand additional out-of-plant and in-plant tests for certification of the NPP for such duties.

In some countries generating authorities have not permitted participation of NPPs in frequency control, although these NPPs are provided with such facilities and designed with such capabilities, because of the still not fully proven impact on the fuel elements. The effect of load cycling on the endurance of fuel is a matter of continuing research. It is known that in marine PWRs where frequent load changes at the rate of 1% per second or more are common, the fuel is relatively derated compared to the land-based PWRs. However, the NPP vendors do not feel the necessity of derating the fuel for NPPs subjected to load cycling following operations if the extent of the duty cycle is within the range encountered in existing power systems (Appendices III, IV and V). French licensing authorities approved participation of PWRs in load following and network frequency control in January 1984 (Appendix III) after extensive tests [16].

It is evident that subjecting the NPP to load follow and frequency control operation will entail additional surveillance and maintenance work on control rods and the associated drive equipment, particularly for LWRs.

Increasing the nuclear component in the power system will therefore require assessment of its impact on the changes needed in operation of the power system. If the decision is to utilize the NPPs as base load stations only, care has to be taken that there is enough cyclic generation capacity available as well as generating units with proper control characteristics to perform frequency control. Insufficient cyclic generation capacity in the form of thermal stations may entail load following operation by nuclear or hydro units, which may not be possible all the time. Absence of sufficient hydro capacity will require more thermal and nuclear capacity to be used for network frequency control. NPPs have better control characteristics than coal fired stations. Since the quantum of power change involved in network frequency control is very small, it may be economically worth while to utilize an NPP for this duty, provided there is no adverse effect on its components. Such a mode of NPP operation has to be decided upon in consultation with the NPP vendor and the licensing authorities. Similarly, a limited spinning reserve to the extent of step load change accommodating capability may be provided in the NPP because of its better response characteristic than that of coal-fired stations. It is judicious therefore to opt for NPPs with built-in capability for load follow and frequency control operation although in operation they may be subjected to base load duty at nominal full power operation most of the time.

Whether to use the NPP for load following and grid frequency control must be decided by the utility concerned, depending upon the conditions existing in the power system. However, it has to be appreciated that the use of an NPP for such duties is not common at present and generally there is no absolute need for this until the nuclear component in power generation becomes a major contributor. The inherent load changing capability of the NPP can be utilized for occasional requirements of the grid.

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Appendix I

CHARACTERISTICS OF A TYPICAL HIGH PERFORMANCE GRID (REPORTED DATA)

1.	Installed capacity	11 930 MW, forms part of an interconnected system of total capacity 70 000 MW.
2.	Generation mix	Nuclear 41%, hydro 33%, thermal + import 26%. For interconnected system as a whole nuclear 15%, hydro 45%, thermal 40%.
3.	Ratio minimum/maximum demand	0.65
4.	Largest unit size	660 MW, 915 MW for the interconnected system.
5.	Largest NPP unit size	660 MW, 915 MW for the interconnected system.
6.	Criterion followed in fixing the quantum of spinning reserve	According to the tripping of the largest unit; support from the interconnected system included.
7.	Quantum of spinning reserve normally adopted	200–300 MW
8.	Type of generation used in spinning reserve	Mainly hydro, with a certain amount of back-pressure generation. NPPs are not used as spinning reserve.
9.	Maximum capacity of spinning reserve in a single unit	Hydro — 20% Thermal — 5%
10.	Time to come to full power or permissible ramping rates for various types of units operating as spinning reserves	Hydro — 30 s Thermal — 100 s
11.	Maximum allowable power transfer through a single interconnection	1245 MW, greater than 10% of the grid capacity.
12.	Existence of any statutory act or contractual obligation that binds the utilities to maintain the voltage and frequency within a prescribed limit and to limit the number of power interruptions and their duration	A joint operation contract between electric utilities.
13.	Normal random frequency variation	±100 mHz

14.	Percentage of time when the frequency is within	
	±0.1 per cent of nominal frequency	90%
	±0.5 per cent of nominal frequency	99.9%
	±1.0 per cent of nominal frequency	99.995%
	beyond ±1.0 per cent of nominal frequency	Negligible, only in extreme faults.
15.	Highest and lowest frequency observed during disturbance	51.5 Hz and 48.2 Hz
16.	Grid stiffness in MW/Hz loss in generation which will cause frequency to drop by 1 Hz without load shedding	1050 MW/Hz 6000 MW/Hz for the interconnected system.
17.	Rate of frequency drop without load shedding when the largest generating unit is lost	0.06 Hz/s for the interconnected system.
18.	Station isolation frequency for NPP and other stations	High 52 Hz Low Not reported
19.	Permitted highest operating frequency on continuous basis	50.1 Hz
20.	Sharing of power system duty by various types of stations	
	Base load	
	Nuclear 70%	
	Coal 20%	
	Hydro 10%	
	Scheduled load follow	
	Coal 45%	
	Hydro 55%	
	Frequency control	
	Hydro 100%	
	Peaking duty	
	Hydro 30%	
	Gas and oil 70%	
21.	Duty of NPP	Base load at maximum nominal power only.
22.	Dead band of governors of stations operating as base load station	0.2 Hz
23.	Typical governor droop characteristics	6%
24.	Required rate of power change for stations participating in scheduled load following and grid frequency control	Hydro 100% in 3–4 minutes.

25.	Percentage of operating time the voltage is within	
	±5% of nominal voltage	99.5%
	beyond ±5% of nominal voltage	Only in extreme faults.
26.	Expected clearing of faults	In 400 kV, 0.1 s In 110 kV, 0.1−0.5 s
27.	Autoreclosure of line breakers at the NPP terminals	Not permitted.

28. Details of load shedding

Load shedding is performed in two stages, each of which has two delay times in two different frequencies. The stages are

	Frequency (Hz)	Delay (s)	Tripped load (%)
(1)	48.7	20	10
	48.5	0.15	
(2)	48.5	20	10
	48.3	0.15	

df/dt relays are not used. Voltage control is not activated in any special manner during load shedding.

29.	Load restoration	Partly automatic.
30.	Frequency of load shedding incidents and average duration	As of 1984 no load shedding incidents had occurred.
31.	Automatic generation control	In use.
32.	Communication and data link	There are on-line communications systems between major generation plants, stations and the central control centre.
33.	Frequency of grid-induced NPP outages	0.3 per reactor year.
34.	Frequency and duration of failure of off-site power at the NPP	No such incident has occurred so far.
35.	Power system co-ordination	Generation and transmission is co-ordinated by a single agency.

Appendix II

CHARACTERISTICS OF A TYPICAL LOW PERFORMANCE GRID (REPORTED DATA)

1.	Installed capacity	6079 MW
2.	Generation mix	Hydro — 21.5% Thermal — 71.67% Nuclear — 7%
3.	Ratio minimum/maximum demand	0.6
4.	Largest unit size	500 MW
5.	Largest NPP unit size	210 MW
6.	Available spinning reserve	Negligible.
7.	System reserve management	Thermal units to follow scheduled load changes and hydro for frequency adjustment. Often the reserves are insufficient to carry out these functions effectively.
8.	Permissible ramping rates	Hydro — 5 to 10% per second Thermal — 1 to 4% per minute
9.	NPP operation mode	Base load.
10.	Interconnections	Interconnected with three smaller neighbouring grids through tie lines at 220 kV level with transmission capacity ranging from 200 to 400 MW. These lines are closed only for part of the time, except with one neighbour where it is almost always connected.
11.	Normal frequency variation	Sustained underfrequency operation around 49.5 Hz is often resorted to. When there are no major disturbances, the frequency lies between 48.5 and 50.0 Hz.
	Per cent of time when f is within	±0.4% (i.e. between 49.8 and 50.2 Hz)
	Per cent of time when f	<49.8 Hz — 72.5% <49.5 Hz — 55% <49 Hz — 35% <48.5 Hz — 5%
12.	Highest and lowest frequency observed during disturbances	51 Hz and values below 47.5 Hz.
13.	Inherent load reduction with frequency	180 MW/Hz. (The neighbouring grid remaining connected has another 100 MW/Hz.)

14.	Rate of fall of frequency when the largest generating unit (500 MW) is lost	0.5 Hz/s (estimated)
15.	Station isolation frequency and generator lockout frequency for NPP and other major thermal stations	47.5 Hz
16.	Highest frequency at which the grid is allowed to operate continuously	50.2 Hz
17.	Distribution of load following duties	Thermal units assigned with scheduled load following duty. Small reserves in several hydro units used for frequency adjustment. Several run-of-the river hydro units are base load operated and some are irrigation constrained.
18.	Expected clearing time of power system faults	100 to 200 ms
19.	Autoreclosures permitted near NPP terminals	No.
20.	Load shedding scheme	Automatic tripping of some feeders on under-frequency introduced only within the last few years. Relay setting varies from 48.6 Hz to 48.0 Hz and the quantum of load shed through these relays amounts to 25% of peak demand.
21.	Load management measures	Staggering of holidays. 15% to 30% power demand cut and 10 to 20% energy cut for industries. Agricultural loads supplied only during specified hours.
22.	Frequency of load shedding occurrence	Almost daily.
23.	Islanding schemes to save NPP during power system emergencies	Under consideration.
24.	Automatic generation control	Non existent.
25.	Automatic tie line control	Non existent.
26.	Frequency of grid-induced NPP outages	~4 per year.
27.	Frequency and duration of failure of off-site power at NPP terminals	~5 per year. 10 to 40 minutes.

Appendix III

CHARACTERISTICS OF STANDARDIZED PWR UNITS (VENDOR DATA)

1.	Standard unit sizes	880 MW 920 MW 1270 MW 1300 MW

Standardized unit sizes down to 440 MW are also available from other vendors.

2.	Frequency band to which the governor is insensitive for base load operation	100 mHz
3.	Turbine overspeed trip set point	109%
4.	Reactor trip by turbine trip at full load	No trip for 900 MW unit. No trip for 1300 MW unit if load is lower than 40% full load.
5.	Effect of generator output change caused by frequency variation	Movement of control rods takes place. Such cyclic changes in reactor power and movement of control rods will need surveillance of the control rods and drives; life of fuel is not likely to be affected.
6.	Process variables used in reactor power control system	Average temperature of primary coolant (T_{av}).
7.	Station isolation frequency	47 Hz
8.	Reactor trip set point for grid underfrequency	46.5 Hz
9.	Load rejection	On load rejection the control rods are subjected to large movement because of change in T_{av}. Power run-back is not initiated automatically.
10.	Steam dump capacity	87% full power Rate of opening: Quick speed 1–2 s Slow speed 7 s
11.	In islanded or house loading operation	Steam dump closes at 20% nominal power.
12.	Time duration limit for house loaded operation	No limit.
13.	Time the NPP can stand three-phase short circuit	0.9 s (This figure appears to be based on undervoltage protection for the pump motors or reduction of primary coolant flow. However, to avoid excessive stress on turbo-generator shaft, the fault should be cleared within 150 ms.)[1]

14.	Autoreclosure of line breakers at generator terminals	Permitted (under certain conditions only).[1]
15.	Effects of voltage and frequency variation on reactor power	Not significant.
16.	Power output limitation in underfrequency operation	Less than 5%.
17.	Voltage and frequency bands for normal operation of auxiliaries	Voltage 0.95–1.06 V nominal Frequency 49.5–50.5 Hz
18.	Target reliability for the on-site power supply system	2×10^{-2} (unreliability)
19.	Assumed reliability for off-site power supply system	0.5 hour duration 5×10^{-2} (unreliability) 24 hour duration 10^{-2} (unreliability)
20.	Maintenance frequency for major components such as diesel generators of the on-site power supply system	Three months or 15 starts.
21.	Capability of participation in grid frequency control operation	Range: ±7% of nominal power Maximum rate: step of 10% nominal power.
22.	Design peak power rating for fuel for scheduled load following and frequency control operations	Same as in the case of stations designed for base load operation.
23.	Effect of load following and frequency control operation on the control rods	Reliability is affected.
24.	Licensing requirement for subjecting NPP to scheduled load follow and frequency control operation	Authorization by the licensing body is required, and was given in January 1984.

Information by courtesy of Framatome, France.

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[1] Comment by the authors.

Appendix IV

CHARACTERISTICS OF STANDARDIZED BWR UNITS (VENDOR DATA)

1. **Standardized unit sizes**

   650 MW and 1000 MW.

2. **Frequency band in which the governor can be made insensitive:**

   In these BWR units the turbine governor is acting as a slave to the reactor; the turbine governor does not sense frequency or power for control purposes; the plant power is controlled by the reactor power control system. The reactor power control system includes a 'frequency control mode'. The frequency controller has a dead band amplifier whose positive and negative dead bands are individually adjustable between 0–1.0 Hz.

3. **Highest frequency of operation**

   The normal operation range is up to 51 Hz; higher frequencies are allowed only for short periods (above 51 Hz, limiters in turbine control will reduce power output).

4. **Full load rejection capability**

   Designed to accommodate full load rejection without reactor scram. Internal recirculation pumps supplied with power from thyristor controlled frequency converters with small overall time constants can alter the recirculation flow rapidly and bring down the reactor power. In some BWRs, control values are used for recirculation flow control.[1] In a load rejection event (from reactor power above 25%) a certain group of control rods is inserted into the reactor core (partial scram) along with recirculation flow reduction to ensure a rapid power run-back.

5. **Effect of random grid frequency variation**

   Since the governor does not sense frequency for power control, the throttle valve opening does not change and transients are not induced through grid frequency variation during normal base load operation.[1]

6. **Recommended station isolation frequency**

   Operation at frequencies down to 49 Hz is permitted for a limited period (10 minutes) — after which the plant is isolated from the grid.

7. **Generator lockout frequency**

   47.5 Hz for 6 s.

8. **Power run-back**

   Power run-back consisting of partial scram and rapid recirculation flow reduction is initiated automatically on load rejection. Run-back rate is determined mainly by the coastdown time for the recirculation pumps. Run-back of recirculation pumps reduces the power to about 60% (when the starting point is full load). Partial scram reduces the reactor power by another 10–15%.

9. **Capacity of steam bypass valves**

   This corresponds to somewhat higher than 100% steam flow.

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[1] Comment by the authors.

10. **Islanded and house load operation**

After transition to house load or islanded mode of operation the reactor power is maintained constant, at the level given in item 8, awaiting restoration of the grid. If this restoration follows within a short time, the plant is prepared for rapid reconnection and power increase to full power again. For protracted grid disturbances, insertion of more control rods is recommended, although this implies that the return to power will take longer. The load following mode of operation is not recommended during house load operation. Power control is performed by the turbine governor system, adjusting the steam flow to the turbine in accordance with the power demand by the reactor auxiliaries. The reactor power is maintained constant at a higher level, the excess steam being discharged to the condenser through the bypass valves to maintain constant reactor pressure.

As regards the reactor, there is no limitation as regards the duration of house load operation, but the turbine manufacturer normally limits such operation to a few hours.

11. **Generator operation after reactor trip**

In a reactor scram event, the generator is not automatically tripped but left connected with the grid. The generator is automatically tripped by reverse power relay, protecting it from motoring.

12. **Time to come to full power after trip**

Provided the turbine is warm it will take 5–6 hours, depending on the need to heat steam lines, feedwater lines and condensate.

13. **Duration over which the NPP can withstand a 3-phase short circuit at the outgoing lines very near it**

150 ms; a fault period exceeding 200 ms may result in plant trip as the generator falls out of synchronism.

14. **Autoclosure of line breakers at NPP terminals**

Discarded because of grid stability problems.

15. **Effect of voltage and frequency variation on recirculation flow**

The static frequency converters supplying power to the recirculation pump motors are insensitive to moderate frequency variations (including a 2 Hz band). They are designed for full power output at a power supply voltage of 90%.

16. **Limitations in power output during underfrequency operation**

Power output of the turbine decreases linearly with the frequency when the plant operates at frequencies below 49 Hz.

17. **Recommended voltage and frequency for continuous full power operation**

Frequency 49–50.25 Hz; voltage 95%–105% nominal.

18. **Schedules for maintenance and inspection of major components such as diesel generators of the on-site power supply system**

Disel generating units are test run monthly, including checks on control functions for auxiliary systems. Twice a year condensate is drained from starting air receivers, together with diesel engine checks (according to manufacturer's manual). Fuel filters are cleaned annually with other engine services according to the manual, and a complete diesel start sequence is also made once a year. Certain checks and inspections are also prescribed on a daily and weekly basis. Similar procedures are followed for other important parts with rather frequent checks but major maintenance is mainly made on an annual basis.

19. **Suitability for use in load following and network frequency control operation**

Designed for such operation, but not yet employed for such duties.

20. Derating of fuel in the case of the above operational modes

The peak rating of the fuel is the same as for NPPs designed for base load operation and no derating is necessary.

21. Effect of above operations on reliability of control rods

Control rods are not normally operated in such mode. For load swings outside the range of recirculation flow, control rods will be operated, however, and thus will require some more maintenance work on control rod drives during the refuelling outage.

22. Effect of large transients such as load rejections and reactor trips on the life of fuel and other reactor components

Full load rejections are not a particular problem for the fuel, as long as the transition to house load operation is successful. The transition depends on the correct functioning of many sistems and components and the margin is very small, i.e. some of these load rejections (maybe 50%) may lead to reactor scram. Still, the fuel is not considered to be a limiting factor.

As for other parts of the plant, the load rejections and possible scrams will have an impact. The 'transient' budget allows around ten scrams per year of plant life, and so a large number of load rejections may affect the plant lifetime.

Each load rejection event will of course also affect turbine plant systems and components, partly the bypass valves, but also other parts, since turbine plant operation at power levels about 40% involves changes in the mode of operation.

Information by courtesy of ASEA-ATOM, Sweden.

Appendix V

CHARACTERISTICS OF STANDARDIZED CANDU PHWR UNITS (VENDOR DATA)

1. Standardized unit sizes

500 MW(e) (in four-unit format), 600 MW(e) (in single-unit format) and 850 MW(e) (in four-unit format). Single-unit designs in 300 MW(e) sizes have also been developed (but have not been built yet)[1].

Comments

Barring 500 MW(e) units, all other unit sizes permit boiling in the reactor core, the outlet quality varying from 1.3% to 4%. All these units, based on boiling of primary coolant in the reactor core, use large-size pressurizers for primary coolant pressure control. Retaining fluid at high pressure and temperature in a pressurizer is an alternative design to that of keeping heavy water in low-pressure storage with large high-pressure charging pumps in operation. The total amount of heavy water in a CANDU of a given size is about the same regardless of pressure control philosophy; indeed the 600 MW(e) CANDU stations with relatively large pressurizers have the lowest specific heavy water inventories.

Plant	Size MW(e) gross	Pressurizer	Specific heavy water inventory (Mg/MW(e))
Douglas Point/RAPP	220	No	~1.0
Pickering A	540	No	0.85
Bruce B	850	Yes	0.85
CANDU 600	678	Yes	0.67

Unit sizes in which there is boiling of primary coolant use constant steam generator pressure in place of programmed pressure as in 200 and 500 MW(e) units. As a result, there is less stored energy in the steam generator at part load and this is a disadvantage in respect of providing spinning reserve and performing load following[1].

2. The frequency band to which the turbine governor can be made insensitive

Two ways of desensitizing the governor to grid frequency are:

(a) Increasing the droop setting

(b) Introducing a dead band in the frequency response of the governor.

Governor droop setting is typically adjustable in the field over a range of about 2–10%. In stable grid systems, such as in Canada, droop values of 4–5% are used. In less stable offshore grid systems, droops around 8% can be used for CANDU stations. Dead bands in governors are not used in Canada but a ±0.3 Hz dead band is being used in one of the offshore stations.

Comment: The droop setting must be selected such that the turbine acceleration in the event of load rejection is within specifications.

3. Highest frequency in operation

This is a characteristic of the turbine and its governor system and can vary from one station to another. Typically, the margin between load rejection overspeed and the overspeed turbine trip setting is quite small (about 1%), so only a slightly higher than normal frequency will be allowed.

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[1] Comment by the authors.

4. Reactor trip due to trip of turbine at full power

The reactor does not trip. The steam generator pressure controller will immediately open the turbine bypass (dump) valves and the atmospheric discharge valves upon detection of a turbine trip, and depending on the capacity of the bypass valves, the reactor regulating system will initiate either a setback (1% per second power reduction) or a stepback (fast power reduction via rod drop) to the poison prevent level of 65% full power. The actions are sufficient to keep all major plant variables below the trip level.

5. Effect of random grid frequency variation

CANDU stations can coperate in two control modes, (a) normal mode, reactor-follow-turbine and (b) alternate mode, turbine-follow-reactor, selectable by the operator.

(a) For the normal mode

(i) Since reactor power follows turbine power, there will be adjustment of reactor power as the turbine power changes. The adjustment of reactor power (5 – 10%) can be handled by the liquid-zone absorber system. Thus movement of mechanical control rods (adjusters and control absorbers) is not required.

(ii) The reactor power is adjusted so as to maintain the desired steam pressure in the boilers; this control loop uses other signals such as turbine power for feed forward action.

(iii) There is no movement of mechanical control rods. In addition, the valves adjusting the liquid absorber levels are designed for a continuous duty cycle. Thus, there is no reduction in fatigue life due to grid frequency variation.

(iv) All experience to date indicates CANDU fuel can withstand a large number of power cycles without detrimental results. The experience in RAPP supports this in terms of fuel performance.

(b) For the alternate mode

Reactor power is fixed and no control rod movement will occur.

6. Recommended station isolation frequency

Typical low-frequency values are 0.933% of nominal frequency for immediate isolation and 0.958% for isolation after 10 s. At high frequencies, there is no automatic action in terms of isolating the station before the turbine overspeed trip at 110%. However, operating procedures call for manual isolation if a small ($\ll$ 10%) and sustained frequency increase is encountered.

7. Power run-back on load rejection

On load rejection, reactor power is automatically run back to the poison prevent level of 65% full power. Depending on the capacity of the steam bypass system, the reactor power reduction may be gradual (1% per second by liquid control absorbers) or very rapid (stepback by partial drop of mechanical control absorber rods).

8. Capacity and speed of operation of steam bypass valves

Some CANDU stations have 100% transient dump capacity (for several minutes) and 70% steady state capacity. This allows full bypass on a turbine trip and gradual reduction of reactor power to the poison prevent level of 65% full power. For such stations, no steam needs to be discharged to atmosphere following a turbine trip, although 10% capacity atmospheric steam discharge valves are provided. At all other CANDU stations the dump capacity is approximately 70% for both steady state and transient conditions; in addition there is a 10% capacity atmospheric steam discharge system. The steam dump valve opening is very fast — a stroking time of 2 s is usually specified.

9. Operation in islanded condition

During islanded operation both the modes of operation mentioned in item 5 are available. However, to minimize transients in the NPP, and thus minimize the risk of outage, constant power operation is preferred, the power level being at least the poison prevent level.

10. Load following operation

In general, CANDU reactors are very manoeuvrable, partly because feedback reactivities are very small and therefore a small amount of control reactivity suffices for large power changes. The reactor components and processes can tolerate rapid power changes. Reactor power change rates up to 60% per minute are provided. The turbine is generally more restrictive than the reactor, typically with hot loading rates of 10% per minute maximum.

Operating experience of CANDU reactors in scheduled load following or grid frequency control has not been extensive. However, it is felt with confidence that the stations can accept step increases in load of at least 5% full power and can follow a daily load cycle of 15 hours at 100%, 3 hours reducing to 65%, 3 hours at 65% and 3 hours returning to 100% full power.

11. House load operation, duration and limitation

The station can run indefinitely on its own house load. If operation previous to separating from the grid had been steady state full power, the reactor would need to be at 65% full power, the poison prevent level, with unused steam dumped into the condenser. If previous operation had been at low power, no steam bypass would be required. A very slow transition (many hours) between the poison prevent level and the low reactor power operating state is possible, eliminating the need to bypass steam in the long run.

Some turbines may have limitations on the length of time they may operate at very light loads.

12. Motoring of generator after reactor trip

Some turbine manufacturers do not permit motoring. However, at most CANDU stations provision for adequate cooling has been made and motoring is permitted. The maximum motoring time period is specified by the poison-out time, which is about 30 minutes.

13. Time to come to full power after trip

Following a reactor trip from steady state full power operation, a CANDU station must be brought back to at least 60% full power, fairly quickly (typically within 30 minutes), to prevent poison-out of the station.

After a short trip outage (less than 30 minutes) the power recovery to about 70% is quite fast, taking only a few minutes. The time to return to full power is considerably longer, around 4–6 hours, because it takes time for the xenon transient to be overcome and for the adjuster rods, which must be withdrawn to offset the xenon, to be reinserted. While the adjusters are not fully inserted, flux distortions force some derating of the reactor.

After a poison outage, if the heat transport system is kept hot, power recovery time can be as little as 4.5 hours to allow for drawing condenser vacuum, warming up the steam piping and the turbine, and loading the turbine. Xenon and flux distribution effects pose no constraint in this case.

From cold conditions, heat transport system warm-up must be added to the time above, making the fastest possible attainment of full power approximately 6 hours.

14. Time over which the CANDU station can withstand a three-phase short circuit at the outgoing lines very near the station

The station breakers are designed to open within five cycles of a fault. If the primary protection logic malfunctions, backup logic will trip the breakers in another 5–8 cycles. The station can tolerate the fault for about 13 cycles. (This is with reference to 60 Hz systems.)

15. Autoreclosure of line breaks at terminals

Autoreclosure of breakers is permitted, but is usually not done for faults near the station.

16. Underfrequency operation of the NPP

CANDU stations can accommodate some degree of underfrequency operation (2%) with no effect on power output. Larger frequency reduction may lead to slight derating of the unit.

17. Voltage and frequency bands within which the auxiliaries are expected to perform as per design.

The bands vary from station to station. The voltage range is typically ±10%. The frequency range and duration at one of the offshore site, which is typical, are:

48.5 Hz to 50.5 Hz	continuous
48 Hz to 51 Hz	90 minutes
47.5 Hz to 52 Hz	20 minutes
46.5 Hz	45 seconds
46 Hz	30 seconds

18. Recommended voltage and frequency bands within which a standardized unit is expected to perform (as base load station) as per design

In Canada, continuous operation at full load with voltage variation of ±10% and frequency variation of ±2% is usually specified. In offshore sites somewhat larger variations are usual, e.g. frequencies lower by 3% of nominal value.

19. Reliability of the on-site power supply system

Unavailability of normal class III on site diesel generator power supply is 10^{-3}. Additional emergency power backup generators of smaller capacity give an unavailability of on-site power of 10^{-5}.

20. Frequency and duration of failure of off-site power system assumed for design of on-site power supply system

Three categories of off-site power system failure are distinguished based on the duration and frequency of the failure.

Category A	a short-term loss of power where power remains available at the switchyard and can be restored to the unit within 10–30 minutes by station personnel by closing or opening certain breakers. Failure frequency is one event per year.
Category B	a failure in which power from the grid cannot be restored within 2–6 hours without significant effort by personnel outside the station. Failure frequency is 2×10^{-2} events per year.
Category C	a failure in which power from the grid cannot be restored within 6–24 hours without repair of system components. Failure frequency is 3×10^{-3} events per year.

21. Frequency of maintenance recommended for most essential components of the on-site power supply system

Diesel generators are tested every two weeks and are repaired immediately if any fault is detected. In addition, routine maintenance is performed as specified by the manufacturer.

Inverters are not tested as they operate continuously. Any failure detected is annunciated and repaired immediately. No routine maintenance is needed.

22. Advisability of permitting CANDU units of standardized design to participate in grid frequency control operation, permissible power change and rate of power manœuvring

CANDU reactors have a good response characteristic. A brief test on a relatively unsteady grid, resulting in reactor power swings of ±3 to ±4% every minute or so, shows little effect on the process variables or control systems. It is felt that the station can handle larger swings without difficulty.

23. Whether derating of fuel will be necessary should an NPP designed for base load operation be subjected to scheduled load follow and gain frequency control operation

Derating will not be necessary. The design peak rating for CANDU fuel will be the same for base load operation and for load cycling or frequency control operation.

24. Is reliability of components, particularly of control rods, likely to be affected because of scheduled load follow and/or frequency control operation?

No component in a CANDU station has been identified whose reliability will be adversely affected by load cycling and/or frequency control operation.

Simplicity in the design of mechanical control rods and associated drives and the low pressure (atmospheric), low temperature (60°C) environment within which reactivity devices operate all help to achieve good reliability.

25. Effect of reactor trips and other major disturbances such as load rejection on the life of fuel and other components

CANDU fuel has a core residence time of less than a year on average. It is known to be very tolerant of shutdowns and subsequent power recovery. (Some bundles have been subject to hundreds of full power cycles.)

The reactor is designed, for economic and safety reasons, to have very few upsets requiring reactor trips. Fuel can tolerate far more trips than the reactor is expected to have.

26. Is any special licensing required for subjecting the standardized CANDU to scheduled load follow and/or frequency control operation?

It is not anticipated that formal re-licensing of a station will be required. However, this would depend upon the regulatory authorities in each country. Safety analysis would be available to ensure that all safety aspects continue to be fully satisfied.

Information by courtesy of Atomic Energy of Canada Ltd.

Appendix VI

SPECIFICS OF GRID DATA SHEET

1. Installed capacity.
2. Capacity factor, average.
3. Generation mix, nuclear, thermal, hydro.
4. Demand factor, average.
5. Quantum of maximum import or export of power through interconnection.
6. Number of tie lines, and maximum allowable power transfer through a single interconnection.
7. Largest unit size.
8. Largest NPP unit size if NPPs are operating in the grid.
9. Criterion followed in fixing the quantum of reserve.
10. Quantum of spinning reserve excluding import of power.
11. Type of generation used in spinning reserve.
12. Maximum capacity of spinning reserve provided in a single unit.
13. Time to come to full power or permissible ramping rates for various types of units operating as spinning reserve.
14. Sharing of power system duties, i.e. base load, sheduled load following, network frequency control and peaking between various types of stations.
15. Load change capability and power response characteristics of existing generating units.
16. Whether tripping of tie lines is automatic. If so, setting of various parameters such as frequency, voltage, power flow for initiating automatic action.
17. Normal random frequency variation.
18. Percentage of time when the frequency is within
    - (i) ±0.1% of nominal frequency
    - (ii) ±0.5% of nominal frequency
    - (iii) ±1.0% of nominal frequency
    - (iv) beyond ±1.0%.
19. Highest and lowest frequency observed during disturbances.
20. Grid stiffness in MW/Hz, i.e. how much generation loss will cause the frequency to drop by 1 Hz without load shedding.
21. Rate of drop of frequency when the largest generating unit is lost.
22. Rate of fall/rise of frequency when interconnection is severed and import/export of power stops.
23. Isolation frequencies of generating units.
24. Dead band of governors of stations operating as base load units.
25. Typical governor droop characteristics of various types of stations.
26. Percentage of operating time when the voltage is within
    - (i) ±5% of nominal voltage
    - (ii) beyond ±5% of nominal voltage.
27. Reactive power management scheme, and deployment of reactive power compensation devices. Whether series capacitors are used with transmission lines; whether generators have to operate with leading reactive capacity or close to the stability limit.
28. Frequency of incidents involving trip of generating units.
29. Frequency of incidence of tie line tripping.
30. Frequency of incidence of transmission line faults.
31. Expected clearing time of faults.
32. Reliability of grid protection equipment in clearing the faults.
33. Autoreclosure permitted or not.
34. Automatic generation control in use or not.
35. Load shedding
    - (i) Total quantum of load that can be disconnected automatically
    - (ii) Frequency at which automatic load shedding starts

  (iii) Levels of underfrequency for load shedding
  (iv) Time delay associated with load shedding relays
  (v) Redundancy or coincidence arrangement provided in load shedding relays to ensure reliability and avoidance of spurious trips
  (vi) Reactive power management and voltage control during load shedding
  (vii) Load restoration procedure.

36. Frequency of load shedding incidents and their average duration.

37. Islanding schemes, and grid operating strategy during islanded mode of operation. Duration of islanded mode of operation.

38. Frequency of grid collapse and average duration. Maximum duration recorded.

39. Restoration procedure after grid collapse. If any special steps are taken when the grid contains NPPs.

40. Grid-induced outage rate of NPP, if existing.

41. Frequency of Class IV failure incidents at the NPP, if existing; average and maximum duration of failure.

42. Energy control centre/load dispatch centres:
Facilities and information available for control and co-ordination at central, regional, local levels.

43. Communications:
Communication and data telemetry arrangement between load despatch/energy control centres, major substations and generating units.

44. Network information available at the NPP and other large generating units.

45. Instrumentation and recording devices available for monitoring important parameters during normal operation and disturbed conditions.

46. Power system management and co-ordination:
Single or multiple agency. Organization to plan and execute power system expansion, power system control, contingency operation, generation scheduling, maintenance scheduling, exchange of power between interconnected grids, etc.

47. Results of power system studies including
  (i) Load flow studies
  (ii) Transient stability studies
  (iii) Long duration system dynamics studies involving loss of generation.

Appendix VII

SPECIFICS OF NPP CHARACTERISTICS TO BE OBTAINED BY THE PROSPECTIVE OWNER FROM THE VENDORS

1. Available standardized unit sizes.
2. Capital cost per kW for various unit sizes.
3. Fuelling cost per kW·h.
4. Expected loss of heavy water per year (PHWRs only).
5. Expected operating life.
6. Length of fuel cycle at nominal full power (LWRs only).
7. Feasibility and implications of coastdown operation (LWRs only).
8. Expected downtime due to refuelling (LWRs only).
9. Frequency of routine inspection and maintenance and expected shutdown time for such activities.
10. Power system duties the NPP is capable of performing, i.e. base load, scheduled load following, network frequency control.
11. Normal frequency dead band of speed governors when the NPP is to be operated as base load station.
12. Transients in the NPP, movement of control rods caused by grid frequency variation beyond the dead band.
13. Effect of such transients on the fuel, control rods, primary structure; need for additional instrumentation for surveillance in critical areas; requirement of additional maintenance effort in selected areas.
14. Possibility of increasing the frequency dead band of the speed governor, and the maximum width of the dead band.
15. Whether the NPP is proven for scheduled load following and frequency control duties; details and extent of operating experience.
16. Effect of such operating duties on reliability of control rods and associated drive equipment.
17. Effect of such operating duties on life of fuel, primary structure and other components of NPP. Whether derating of fuel will be required.
18. Load change capability; rate and range, including step load change.
19. Time constant between change in reactor power demand and corresponding change in turbogenerator output power.
20. Mode of normal reactor power control, reactor-follow-turbine or turbine-follow-reactor; feasibility of conversion of turbine-follow-reactor mode to the other.
21. Requirement of specially sophisticated (computer-based) reactor power control system, reactor protective system and core power monitoring system for effective participation in scheduled load follow and network frequency control operations.
22. Time to bring the NPP to full power from cold condition.
23. Time to bring the NPP to full power after a trip while the turbine is still warm.
24. Time to reach full power after first commissioning or after refuelling (LWRs only).
25. Expected number of trips during first year of operation (based on operating experience).
26. Capability to come to house load after full load rejection.
27. Power run-back capability and its mechanism.
28. Expected percentage of successful house loading operation (without NPP trip).
29. Feasibility of operating the reactor at higher power while at house load and time limit for such operation; reasons for such limitations.
30. Minimum power at which the reactor can be operated at house load conditions.
31. Time limit for house load operation; reasons for limitation.
32. Mode of reactor power control during house load operation.
33. Normal voltage and frequency band recommended for continuous operation at nominal full power; details of limited operation beyond the recommended band; reasons for limitation.

34. Highest frequency the NPP can be operated at full nominal power so that full load rejection does not lead to NPP trip.
35. Whether turbine trip at full power leads to NPP trip.
36. Isolation/minimum operating frequency of the NPP.
37. Time over which NPP can stand short circuit in the grid very near its location without trip, loss of synchronization or damage to the equipment.
38. Whether provision of automatic house loading on undervoltage exists.
39. Turbine loading rate.
40. Speed of operation of turbine stop valve, throttle valve and governor valve.
41. Turbine speed rise after full load rejection and overspeed trip setting.
42. Normal recommended setting of turbine load limiter, lowest obtainable setting.
43. Restrictions in turbine operation under varying frequency conditions.
44. Restrictions in operating the turbine at house load; time duration limit.
45. Capacity of bypass valves, including dump into condenser and discharge into atmosphere.
46. Speed of operation of bypass valves.
47. Restrictions imposed by condenser on the dumping rate and duration.
48. Generator characteristics, including details of excitation control system, whether fast-acting solid state control system is used; operating capability with leading reactive capacity; power angle at stability limit; capability of voltage control; setting of generator lockout relay.
49. Whether generator is allowed to remain connected to the grid after NPP trip; method of disconnection.
50. Voltage drop in transformers (regulation).
51. Design voltage drop in cables for full auxiliary load.
52. Provisions of on-load tap changing and percentage of taps on main and unit auxiliary transformers.
53. Provision of separate startup transformer with or without on-load tap changing.
54. Recommended voltage and frequency band for normal operation of NPP auxiliaries; range of limited operation.
55. Minimum startup voltage for the auxiliaries.
56. Recommended setting of undervoltage protection for auxiliaries.
57. Limitations in duration between starts and frequency of starts for high-power auxiliary pump motors, e.g. primary coolant circulating pump motors (PWRs and CANDU PHWRs).
58. Whether auto transfer of loads is provided between unit auxiliary transformers. Whether loss of half of auxiliaries due to unsuccessful auto transfer (during load rejection or generator trip) leads to NPP trip.
59. Whether automatic testing of the logic of the reactor protective system is provided. If not, recommended frequency (daily, weekly, etc.) of checking.
60. Transient budget: Number of full power scrams tolerable by fuel during one cycle, and primary structure for the operating life.
61. Target reliability for the on-site power supply system.
62. Maintenance and test run schedules for major components such as diesel generators, motor generators.
63. Results of simulation studies and test results for an NPP of similar design for full load rejection, turbine trip at full power, step load change, power ramping rates, etc.

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