Nuclear Power and its Fuel Cycle

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Interaction of Grid Characteristics with Design and Performance of Nuclear Power Plants

A Guidebook

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1983

INTERACTION OF GRID CHARACTERISTICS WITH DESIGN AND PERFORMANCE OF NUCLEAR POWER PLANTS

A Guidebook

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FOREWORD

Safe and economic operation of nuclear power plants requires an off-site electric power supply system with a capacity adequate to provide the necessary support for safe start-up, running and shut-down of the plant, a grid capable of dispatching the load and having stable characteristics, and a protection system which keeps disturbances at a low level and of short duration and which prevents disturbance propagation through the system. Such requirements involve considerable expenditure on the acquisition of adequate equipment and the provision of supporting capacity and may be beyond the investment capabilities of the electric utilities of some developing countries. In such countries, the system capacity typically lags behind the demand; the grid characteristics give rise to fluctuations because of inadequacies in the control equipment; and the protection system has poor co-ordination and/or reliability, with excessive fault clearing time. These features are clearly unsuitable for safe and economic operation of nuclear power plants and could represent a severe constraint on the use of nuclear power for electricity generation in developing countries.

The purpose of this Guidebook is to advise engineers, designers and operators of electric power systems in developing countries on the type of problem they may encounter when expanding their power systems by the addition of a nuclear power plant.

The text of the Guidebook is divided into six sections: Section 1 presents an introductory overview, detailing the objectives of the Guidebook and giving general concepts and definitions. Section 2 contains a summary and conclusions. Section 3 describes the relevant design characteristics of proven nuclear power plants which are currently available for export. Section 4 discusses the interdependence of grid and nuclear power plant and suggests measures for mitigating possible operational problems. Section 5 describes those actions which should be considered by the owner of a nuclear power plant before its introduction into the power system. These actions identify the operating characteristics of the electric power system and provide the basis for preliminary discussions with potential suppliers. Finally, the Appendix reports some relevant examples of operating experience.

This Guidebook has been prepared within the framework of a series of technical documents compiled by the IAEA's Division of Nuclear Power. Some of these have already been published, for instance: Manpower Development for Nuclear Power: A Guidebook (IAEA Technical Reports Series No. 200, 1980), Economic Evaluation of Bids for Nuclear Power Plants (IAEA Technical Reports Series No. 175, 1967), Technical Evaluation of Bids for Nuclear Power Plants: A Guidebook (IAEA Technical Reports Series No. 204, 1981), and Guidebook on the Introduction of Nuclear Power (IAEA Technical Reports Series No. 217, 1982). Supplementary guidebooks are under preparation; they treat subjects such as: Control and Instrumentation of Nuclear Power Plants, Nuclear Power Project Management, and Bid Specifications.

Appreciation is expressed of the valuable contributions of W. Aleite (Kraftwerk Union, Federal Republic of Germany), G. Ghosh (Rajasthan Atomic Power Station, India) and M. Nelken (Israel Electric Corporation Ltd., Israel). Thanks are also due to D.J. Love (Bechtel España, Spain), R.N. Carson and F.Y. Tajaddodi (Bechtel Power Corp., Los Angeles, United States of America), R.N. Ray (Bhabha Atomic Research Centre, India), W. Bayer (Siemens AG, Federal Republic of Germany), H. Kürten (Kraftwerk Union, Federal Republic of Germany) and R. Weaner (Department of Energy, United States of America) for a review of the text and for constructive comments.

CONTENTS

1. INTRODUCTION

Faced with the need of achieving the highest possible efficiency in the utilization of primary resources, power system managers should consider nuclear power plants (NPPs) as a viable alternative or addition to their present fossil fuel or hydroelectric plants.

Problems of operating a NPP within an electric grid of limited capacity have long been a serious concern to electric utilities because of the grid's direct bearing on the starting and running of the NPP.

Some of these problems fall within conventional electric system management and are therefore not a subject of this Guidebook. Some of these problems, however, will be mentioned wherever they have a direct bearing on NPP operation. While, in fact, essentially focused on nuclear aspects, this Guidebook cannot totally ignore problems the solution of which, although conventional, could ease and accelerate the introduction of nuclear energy in a developing country. Therefore, load studies, load management, short-circuit studies, voltage and frequency studies are discussed only to the extent that the demands for NPPs may be more restrictive than those for fossil plants. Large power systems have successfully accepted NPPs within their electric grids, but smaller power systems, which typically exist in developing countries, will face problems unique to NPPs because these have special features and important safety systems which are necessary for safe reactor shut-down and require a high level of off-site power support.

Figure 1 illustrates the present and projected system capacities of the present (1980) 110 IAEA Member States. During 1980, the power systems of about 20 Member States (those with a capacity of more than 12 000 MW(e)) had an electric system capacity which could easily absorb a large NPP on its grid. However, 60 Member States (having power systems with a capacity of below 2000 MW(e)) would face extreme problems in attempting to integrate a NPP into their grid. Twenty Member States (power systems of between 2000 and 6000 MW(e) capacity) may adapt nuclear power more easily, and the remaining ten Member States (power systems of between 6000 and 12 000 MW(e) capacity) should have minimal difficulties.

Strong caution has been expressed concerning typical system characteristics to be considered, since it must be recognized that each power system has unique characteristics and most likely will require solutions which are necessarily system specific. This Guidebook cannot provide solutions which can be applied directly to single-case problems. It provides general guidance, describes some typical problems and suggests corrective actions so that planners, designers and operators of electric utilities in developing countries can identify in good time critical problem areas to be carefully considered when tender specifications are established and supply contracts negotiated. Regarding possible remedial

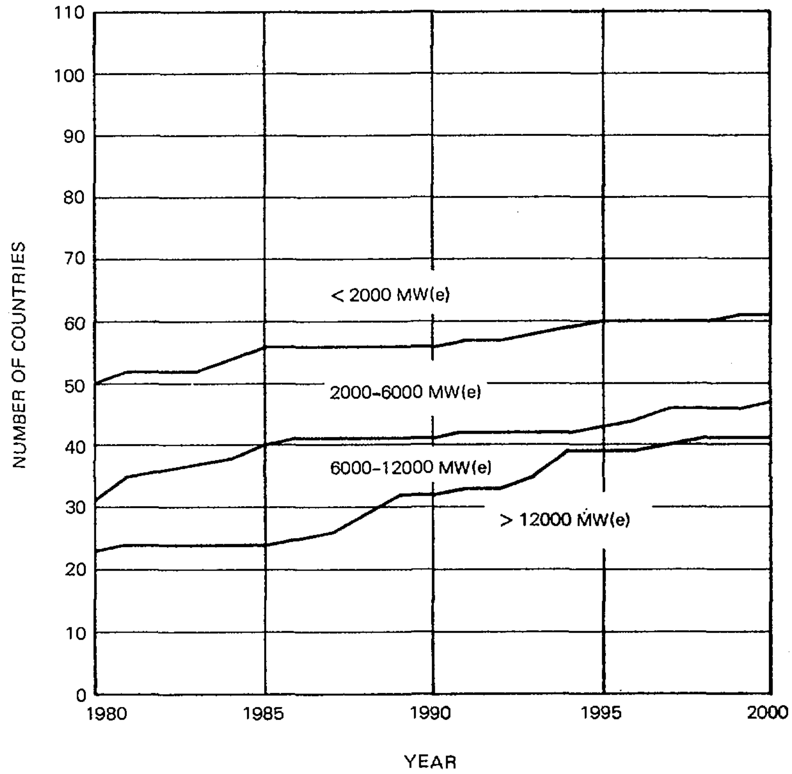

FIG.1. Distribution of national electric system capacities in IAEA Member States.

actions suggested in this Guidebook, its users should bear in mind that the viability of the proposed solutions for their specific situation should be verified, balancing the possible improvements against the financial commitments they may involve. In this respect, throughout the Guidebook the term recommendation is intentionally avoided, since the users should not be directed to any solution without having first evaluated its viability through a cost/benefit assessment.

1.1. Definition of grid characteristics

For the purposes of this Guidebook, it is convenient to recognize that in large interconnected systems the electric grid is generally stable and has adequate capacity to provide the necessary power to assure safe start-up, operation and shut-down of a NPP. However, this Guidebook is directed towards those power systems which do not have such capacity, but which have the capability to be expanded and which have characteristics suitable for NPPs. In order to differentiate between such systems, mention is made in the text of high-performance and low-performance systems.

A high-performance system capable of performing the necessary responses to load and generation trends and perturbations will normally have the following characteristics:

– Adequate grid interconnection, involving multiple parallel lines
– Adequate reserve margins, especially spinning reserves
– Modern load dispatching centres in operation
– A reliable high-speed protective system continually in operation.

With the above capabilities, the grid
– maintains narrow limits of frequency and voltage fluctuations
– does not permit prolonged off-nominal frequency and voltage operation
– keeps disturbances and transients to short duration, and prevents their propagation throughout the system.

A low-performance system would have much lower capabilities, such as:

– Inadequate number of tie lines in the grid
– Inadequacy of system reserve, particularly spinning reserve
– Inadequacy of protective relays capable of fast fault identification
– Improper relay co-ordination
– Absence of fast-acting circuit breakers for quick fault clearance
– Inadequate voltage control equipment
– Inadequate generation control and load-shedding schemes for system frequency regulation or total absence of them.

With the above limited capabilities the grid
– may experience voltage and frequency fluctuations of high magnitude
– has long periods at off-nominal frequency and voltage conditions
– has frequent and/or extended unscheduled generation and/or transmission outages.

1.1.1. Grid reliability

The degree to which the grid can maintain an uninterruptible power supply is the measure of grid reliability.

While total grid power failure is a rather unlikely event even in a low-performance grid, power failure in important nodes of the high-voltage grid, particularly at the points where the NPP will be connected to the grid, may be experienced more frequently than once a year in a low-performance grid. Under these conditions, provisions of additional reinforcements of the on-site auxiliary power supply of the NPP may have to be contemplated in order to meet the overall reliability requirements.

1.1.2. Grid quality

Voltage and frequency stability is indicative of the quality of the grid power supply. It is difficult, however, to establish criteria and to classify the performance of a grid in terms of its voltage and frequency deviations versus time. In this respect, the values reported herein are not meant to represent standards but rather convey an order of magnitude to be used for a qualitative appreciation. In a low-performance grid, frequency deviations in excess of 1% of nominal value are experienced with regularity more frequently than weekly. During these events, the frequency remains at off-nominal value for more than 'a few minutes'. The boundary of 'a few minutes' is the time necessary to bring the frequency to nominal value, either by using spinning reserve, or by starting hydro-units, or by cutting in new coal mills in the case of thermal units. These reserves, with the exception of spinning reserve which can be mobilized in a few seconds, can be started, synchronized and loaded within 5–10 minutes, which means that frequency deviations must be corrected at least within this time. In a low-performance grid, the voltage may vary by more than 10% of nominal value and remain at off-nominal conditions for more than 10–15 minutes. These events may happen more frequently than once a week. Within these time boundaries, it should be possible to restore voltage by bringing additional reactive power-controlling equipment into service.

1.1.3. Grid protection

Following an electric fault, the grid protection system should be capable of clearing the fault in a short time so that the rest of the grid remains healthy. Short circuits should be cleared within 100–150 ms, which means that the associated voltage dip should not persist longer than for 5–8 cycles. In a low-performance grid, the fault-clearing time is frequently in excess of 200 ms.

1.2. Electric power system characteristics

For the load requirements of an electric power system, generating capacity performing base-load and load-follow operations is needed. While base-load generation is used to meet the off-peak demand of the system, load-follow capacity is necessary to meet the following system requirements:

- *Scheduled load-follow operations.* These load changes may occur daily and the grid load generally comes down to 50% of nominal power during the low-demand period. Power change rates generally remain between 0.1 and 1% of nominal power per minute.

- *System regulation.* This is required to compensate for the dynamic load changes and generally occurs with a frequency of several times per day; normally, it remains within a magnitude range of 3–5% of the plant's nominal power and within a rate-of-power change of 1% of nominal power per minute. These load changes are usually prompted by the load dispatch optimization strategy.
- *Network frequency control.* This is required to compensate for the random load changes of small magnitude; typically, it remains within a few per cent of the plant's rated output (frequency control band) and is taken care of by the turbine frequency control system.
- *Contingency operations.* These load changes are usually prompted by grid system upset or fault conditions and require provisions for adequate spinning reserve in the supply system. Spinning reserve is the amount of load pick-up a unit can supply immediately when operating at reduced power level. The spinning reserve assigned to any given plant depends on the mixture and size of the units on the grid.

A high-performance electric power system would have enough generating capacity to meet the demand, a grid capable of efficiently dispatching the power generated at any time, and adequate capability to keep transient conditions at such a level and duration that equipment is not damaged and users are not disturbed.

Transients are caused by electric faults and by the impossibility of the supply system to follow the actual load demand on the grid. These transient conditions determine grid frequency and voltage fluctuations.

- Supply/demand mismatch leads to an imbalance of active and reactive power in the system, and to grid frequency and voltage deviations from nominal values. Under these conditions, each generating unit of the system must be prompted by a loading signal into generating its own share of active and/or reactive power in order to re-establish nominal load conditions in the system.
- Electric faults and consequent short circuits cause a voltage dip and an over-current whose magnitude and duration depend upon the type of fault and the ability of the protection system to clear the fault within a short time.

These events will basically determine the following situations.

(a) Imbalance of active power generates off-nominal frequency conditions.

- The speed of the turbine deviates from its rated value and may approach resonant speed values at which high vibrations may induce blade failures in the low-pressure turbine buckets. Turbine operation at off-nominal frequency is rigorously restricted (see Section 4.1.1.3).

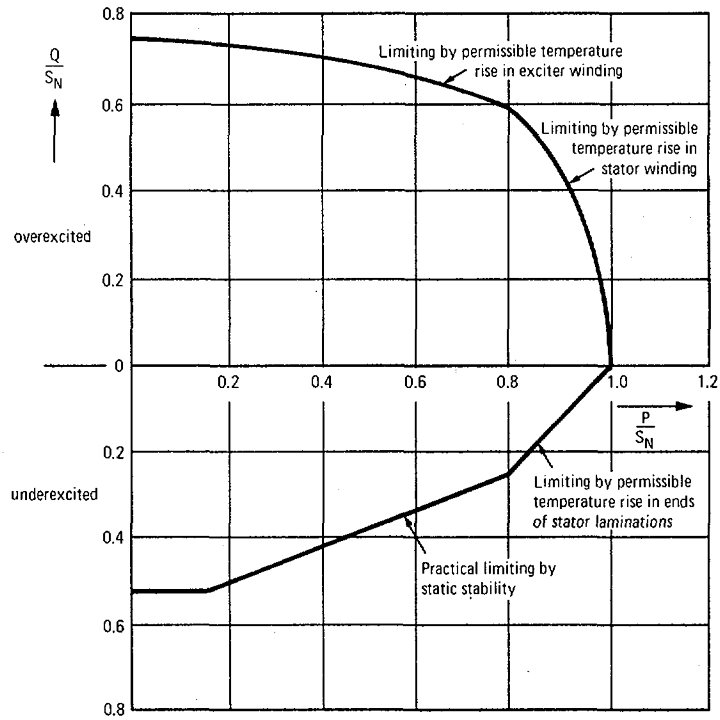

FIG.2. Typical diagram of generator output, valid for $\cos\varphi = \cos\varphi$ *nominal.* P *= active power,* Q *= reactive power,* S_N *= nominal apparent power.*

(b) *Imbalance of reactive power generates off-nominal voltage conditions.*

– Each generating unit must be able to produce or accept an adequate amount of reactive power, as dictated by the load dispatcher, for grid voltage control. It must be ensured that, in doing so, the generator is not overloaded by producing or accepting too high a reactive power, in conformity with the limitations imposed by the manufacturer (see Fig.2).
– The phase angle between the generator and the grid voltage changes; it should not exceed specified values or else the generator will loose step and cannot remain synchronized to the grid.

(c) *Electric faults lead to transient undervoltage and overcurrent conditions* which adversely affect plant operation and are detrimental to important plant equipment.

– Extreme short-circuit conditions in the proximity of the power plant should not persist for more than 5–8 cycles or else the torsional fatigue of the turbogenerator shaft and the stressing of the stator winding will exceed the limitations for safe operation.

From the above, it follows that voltage and frequency deviations from nominal values are recurring events in electric grids. Their magnitude and frequency of occurrence will depend, however, upon the causative situation and the characteristics of the power system, and may vary from narrow band fluctuations and transient conditions of short duration in a high-performance system to large variations and prolonged off-nominal conditions in a low-performance system. In conclusion, the ability of an electric power system to safely absorb the integration of a NPP into its grid will depend on its capability of maintaining an uninterrupted supply while keeping frequency and voltage deviations within small bands and of short duration. These conditions are met if:

- the expansion of the generating capacity of the system is properly planned and implemented in good time, and adequate reserve is provided in the system, especially spinning reserve
- the transmission system is continually reinforced to provide reliable routes for power dispatch and distribution
- efficient generation control is realized by a strategy of economic dispatch optimization
- the voltage profile at critical points of the system is ensured by adequate reactive power control equipment
- a high-speed, reliable and well co-ordinated protection system is continually in operation
- efficient automatic load shedding and load restoration schemes exist.

The above-mentioned requirements are capital-intensive and represent significant additions to the already high investments associated with a NPP. Consequently, the introduction of a NPP into a low-performance system will involve unprecedented requirements in system upgrading whose economic implications must be carefully accounted for in a cost/benefit assessment when performing a nuclear power feasibility study.

2. SUMMARY AND CONCLUSIONS

When considering the expansion of the electric power system by the addition of a new unit, the utility must find answers to the following questions:

- What is the most economic size of the additional unit?
- Is the operating performance of the envisaged unit adequate to meet the load requirements of the system?
- What can be done to mitigate the problems associated with the mutually induced plant/grid dynamic interaction?

These problems will be even more important if the system has limited capabilities and if its expansion is to be made by a first NPP, which will generally be the largest unit operating in the system and probably represent the largest investment the utility has ever made in a power project. These problems will typically be faced by electric utilities in developing countries at the outset of a nuclear power programme.

Before addressing the above questions, it is convenient to recognize that NPPs have special characteristics whose implications must be carefully considered at a very early stage as they may affect the electric grid and may themselves be affected by it. Relevant considerations include the following points:

- Unlike fossil-fuelled power stations, NPPs cannot be easily tailored to the requirements of operators. Nuclear steam supply systems (NSSS) generally exist as proven, licensable designs of large size. These large sizes introduce economic penalties regarding the provision of additional reserves in a low-performance system for frequency control and quick system recovery after an abnormal occurrence. The investments associated with such provisions must be assessed on a cost/benefit basis against the economy of scale for units of large size.
- To supply and distribute essential power to the NPP safety systems during normal operational states, and during and after accident conditions, the on-site power supply and its emergency system must be engineered so as to have a reliability consistent with all the requirements of the safety systems to be supplied. Removal of residual heat for safe plant shut-down requires an uninterruptible and stabilized auxiliary power supply which must be available at any time during the NPP lifetime; this is a requirement of safety significance. In a low-performance system where the reliability of the grid power supply may be low, the on-site power supply reliability shall be such that a high overall reliability is achieved. This condition may call for additional provisions and for redundancy.
- Mainly designed for operation in high-performance grids, NPPs do not tolerate prolonged operation at off-nominal voltage and frequency conditions. These occurrences are not uncommon in low-performance grids. Therefore, appropriate and sometimes extensive grid system improvements and reinforcements may become necessary.
- Because of the large size of components, the special construction requirements, the impact of radiation and the more stringent safety requirements of nuclear power plants, the material stresses under thermal cycling conditions are more critical for NPPs than for conventional fossil-fuelled units. The number of power cycles and their intensity and gradient must not exceed the permissible limits since this may result in shortening of the plant lifetime. Hence limitations are imposed on the power-change capability of NPPs and the permissible changes must be verified against the expected load-change requirements of the

grid. These limits require that NPP operating procedures be strictly adhered to by the operator.

– System load requirements may necessitate special operational features (i.e. load-follow capability) to be introduced in NPP design. The economic significance of such design characteristics must be carefully considered at a very early stage. Preliminary discussions with potential suppliers are an absolute necessity.
– Inspections, repair and maintenance, and off-load refuelling (for LWRs) require provisions of adequate reserves in the supply system as well as capable management to devise appropriate load strategies of the other generating units in order to ensure system stability during prolonged NPP down-times.

2.1. Size selection of nuclear power plants

The high safety standards to which NPPs are licensed for operation require complex engineered safety systems and reliable auxiliary systems which are unprecedented in units of conventional types. The investments associated with these systems penalize the capital costs of NPPs as compared with fossil-fuelled plants of the same capacity. The economy of scale has consequently a major impact on NPPs and this is the reason why NPPs have developed in a range of rapidly increasing unit size. At present, commercially available designs of NSSS may still be too large for the electric grid of many developing countries (see Fig.1) which may not be able to ensure system stability when the NPP is not available. At present, a number of manufacturers supply commercially available NSSS.[1] They would normally supply equipment in the large size range. In principle, a manufacturer may be willing to bid for units in a small size range, but such plants should be regarded as the first ones of a kind for which economics, licensability and reliability may still be open issues. At present, the only proven NPP types commercially available for export include PHWRs, PWRs and BWRs. The minimum size range at which these NSSS are manufactured and which may be termed as proven is 450–600 MW(e).

Nuclear power plants have the lowest marginal fuel cost of all types of power stations other than run-of-river hydro power plants and their continuous operation at nominal power is therefore the utility's first choice for economic electricity generation. However, the size of the power system in some developing countries may be so limited that its off-peak load demand is too low to permit constant load operation of the NPP. In this case, the need of providing some load-follow capability will of necessity add to the plant cost because of additional design and engineering complexity as well as the required instrumentation and degree of automation in the plant control system.

[1] This is extensively discussed in the Guidebook on the Introduction of Nuclear Power (Technical Reports Series No.217, IAEA, 1982) to which reference is made for complete information.

In conclusion, the size selection should be a factor in all implications associated with making NPP operation viable in a low-performance system. Therefore, the following points should be carefully considered:

- Cost of extensive NPP engineering, such as load-follow capabilities, additional equipment, adequate instrumentation and control system, and effective protection system to withstand transient conditions from the grid, to ensure adequate performance and to guarantee the designed plant life.
- Cost of meeting the increased reliability requirements for the on-site emergency power supply to ensure the performance of the essential safety functions of the NPP.
- Cost of maintaining grid stability when the NPP is not available. This is comprised of costs for providing additional spinning reserve, establishing effective system generation control, enhancing the performance of the grid protection system, and reinforcing the transmission system.

2.2. Meeting the system load-change requirements

Nuclear power plants are more sensitive to stresses induced by thermal cycling associated with load-follow operation than conventional plants because of their characteristic larger sizes, thicker walls and massiveness of components. Critical points particularly sensitive to these stresses include component walls, nozzles and adjacent areas, tanks of small mass-to-flow ratio, points subject to large temperature changes, etc.

Also improper changes in the fuel power density distribution associated with load-change operation may induce incorrect pellet/clad interaction and lead to some fuel failures. While generation at constant nominal load will provide the most economical operation of NPPs, it must be recognized that when old conventional units with good load regulation performance are scrapped and the share of the nuclear installed capacity is increased by additional NPPs coming on line, the evolving power system characteristics will require that NPPs also provide load-follow service.

When judging the capability of a NPP to respond to the system load requirements, the utility should first perform power system studies and load demand projections to ascertain what operational mode will be reserved to the envisaged NPP. In this respect, the utility must evaluate the typical daily load curve of the system at the time of future NPP commissioning. The expected load-follow capability of the NPP can then be derived with the known peak and off-peak load demand, the rate of load-change requirements of the system and the optimal loading order established for all generating units of the system. In essence, these studies will reveal the loading/unloading pattern which may be reserved to the NPP. A careful NPP design review must verify that the thermal stresses induced by the power changes associated with the expected loading/unloading pattern for the NPP remain within the limitations imposed by the equipment manufacturers both in the NSSS and the BOP.

This analysis is difficult because it requires not only a good knowledge of the present supply system but also an accurate projection of its configuration at the time of NPP commissioning. Considering that the selection of the appropriate design characteristics is a decision to be made at an early stage and that building a NPP may take ten years, the utility must carefully project the expansion of its system over a time span of more than ten years. In particular, the mixture of the other generating units and their combined load regulation capability at the time of NPP commissioning will be essential in establishing what total load-follow capacity will be available to meet the load-change requirements of the system and in selecting the most favourable loading strategy for the NPP.

In selecting the NPP design, the utility must exercise the utmost care in verifying whether the operating performance of the NPP will meet the functional requirements of the power system. This means that the number and type of power changes which the equipment manufacturer guarantees for safe operation should not be exceeded by the operator when running the NPP or else the operating life of the components will be reduced. In essence, if the NPP is not capable to meet all the load-change rates and magnitudes required by the system, the additional requirements will have to be met by the load-follow generating capacity of the conventional units of the supply system; otherwise, additional cycling capacity will have to be installed and the resulting economic penalty must be carefully considered by the planners in their system expansion evaluation. Section 3.5 will provide more information and assist in clarifying the correct approach to these problems.

In reviewing the NPP ability to respond to the functional requirements of the power system, the following points must be considered.

A low-performance power system will typically experience a higher number of critical occurrences than a high-performance system. This will result in a larger number of events inducing off-nominal frequency and voltage conditions at which the NPP may not be able to operate. The system operator must therefore devise a way of protecting the NPP from those transient conditions which cannot be normally withstood. However, the protection should not systematically imply an interruption of generation since this would adversely affect the availability of the NPP in a low-performance system. A plant trip including the reactor should be regarded as a last resort to prevent occurrences which may have safety-relevant effects. During a trip the plant is subject to a high rate of power change, which consumes a part of its operational life. Considering that trips for plant refuelling (in LWRs) and maintenance are 'incompressible' operational requirements, utmost care should be exercised to warrant that the plant is tripped only when needed, thus preventing any unnecessary reduction of plant life. An appropriate system islanding scheme should be engineered which, after a serious grid-induced occurrence, will allow the NPP to remain synchronized to the islanded system without interrupting generation. This system sectioning into subsystems may reduce the load to be served by the NPP; therefore, its generation may have to be reduced accordingly. This requires that in system upset conditions the NPP should be able to perform a quick set-back to predetermined intermediate power levels which must be compatible with the load the NPP will then be serving in the isolated system.

Under particularly severe conditions, it may even be necessary to island the NPP on itself so that it only serves its own auxiliary systems. During this house-load operation the plant generates only its own auxiliary load; once the disturbance has been eliminated, the plant can be re-synchronized and quickly loaded again to nominal power. This operational characteristic of the NPP is extremely important when the initiating event is anticipated to be of a short duration and the loading signal from the dispatcher is expected within a short time.

Of course, these operating features of the NPP will add to the plant cost because of the more complex design and associated engineering. However, these features are important in ensuring a viable operation of the NPP, especially in a low-performance system. The extra costs associated with these operational capabilities must be balanced against the advantage of a better operational flexibility and longer life of the plant equipment. Reference is made to Sections 3.2 and 3.4 for additional information.

In conclusion, the suitability of a NPP to respond to the operational requirements of the power system, particularly in a low-performance system, will depend on the following abilities of the plant: (a) to change its output, (b) to permit quick plant re-start after a trip, and (c) to permit reactor operation at a higher power level than that of the turbogenerator.

To ensure the safe operation of a NPP in a low-performance system, the right course of action aimed at mitigating the problems arising at the NPP/grid interface will be to simultaneously deal with NPP performance by means of a careful design review and with the functional requirements of the power system by means of effective load management and improvement of the grid characteristics. Possible actions are suggested in Section 4.3. However, the viability of these solutions will always have to be verified by the owner of the NPP through a cost/benefit appraisal.

2.3. Integration of nuclear power plants into the power system

When assessing the technical and economic viability of the first NPP, the utility should have at its disposal all the necessary information on the system characteristics and requirements to which the NPP design features and operating performance have to be made responsive. This information is the basis for a correct design selection. During this analysis, all efforts should be made to identify those grid improvements which would be feasible. To properly perform this assessment, the characteristics of the power system in a steady state and its dynamic behaviour in transient conditions must be well known, with adequate statistical confidence. This implies in turn that the prospective owner of the NPP should initiate in good time a comprehensive monitoring and analysis of the system, and keep an updated and retrievable system data storage (see Section 5.1). As an initial step, only the existing supply and transmission system should be considered, i.e. before the introduction of the NPP. The scope of this analysis is to obtain a statistical distribution of the off-nominal values of the grid parameters, their magnitude, frequency of occurrence, initiating events and system configurations. Monitoring should be performed at critical points of the grid, particularly at the connection points of the future NPP to the grid. As the analysis develops identifiable grid characteristics, this information can be applied in the decision-making process of system expansion and/or modification, and in selecting the appropriate strategy for protection system co-ordination and setting.

It is good practice for grid studies and monitoring to be initiated early enough so that the distribution of disturbances, particularly with respect to their magnitude and frequency of occurrence, can be displayed with adequate statistical confidence. The components will then be specified to operate satisfactorily up to a certain off-nominal voltage and frequency as per design practice of the equipment manufacturers. Beyond this point, means should be provided to protect the components.

Standardized NPP designs can withstand frequency and voltage deviations from nominal values up to magnitudes which are typical of a high-performance grid (see Section 3.3.3). However, the deviations are generally higher in low-performance grids, and the NPP owner is advised to inform potential suppliers of his requirements, to discuss every possible design modification, and to request information on costs associated with possible alternative solutions before taking any decisions.

When planning any system expansion by adding a NPP, the economic optimization of the generating system expansion must be evaluated against the constraints of the transmission system. This analysis is necessary to ensure that the grid will be able to efficiently dispatch the power generated by the NPP with adequate reliability and to ensure system stability under all operating conditions within acceptable limits of the loss-of-load probability. To achieve this, an adequate system model must be constructed and tested (see Section 5.4). This model will permit the simulation of the system dynamic behaviour in upset conditions and its response to them. At the same time, sensitive analysis will identify the necessary grid system modifications and reinforcements and suggest

TABLE I. SUGGESTED COURSE OF ACTION FOR INTEGRATING A NPP INTO THE ELECTRIC POWER SYSTEM

<table>
<tr><td colspan="3">Establish grid data bank. Preserve data for retrieval of relevant information (see 5.2.2)</td></tr>
<tr><td colspan="3">Initiate data gathering for analysis of existing system (before NPP operation).
Included are:
● non-monitored data (see 5.1.1)
● data from continuous monitoring (see 5.1.2)
● data from special monitoring and testing (see 5.1.3)</td></tr>
<tr><td colspan="3">Perform in-depth analysis of those grid improvements which may prove economically viable before NPP commissioning (see 4.3.2)
Included are:
● possible interconnection and strengthening of transmission
● load management and flattening of load curve
● suitable load shedding and system islanding schemes
● suitable co-ordination and setting of protection system
● effective load dispatching and communication systems</td></tr>
<tr><td colspan="3">Project system development until NPP commissioning.
Perform sensitivity studies to identify optimal solutions (see 5.3)</td></tr>
<tr><td colspan="3">Model grid behaviour with NPP, including system dynamic simulation in long-term transient conditions (see 5.4)</td></tr>
<tr><td>Evaluate grid-related input to NPP size and design selection such as
– maximum and minimum grid demand
– rate of change of demand
– contribution of other units of the system, their characteristics and limitations</td><td>Assess reliability of the off-site power supply to NPP in terms of frequency of occurrence and duration of power failures</td><td>Assess quality of grid voltage and frequency in terms of maximum and minimum values, fluctuations, duration of prolonged off-nominal conditions and frequency of occurrence</td></tr>
<tr><td>Assess NPP size (see 2.1) and design capability to meet the system load-change requirements (see 2.2)</td><td>Assess the adequacy of the emergency electric power system of NPP and identify additional requirements (see IAEA Safety Guide No. 50-SG-D7)</td><td>See Table II for NPP/grid interaction</td></tr>
</table>

TABLE I (cont.)

Event	Consequences	Remarks
Drop in frequency (see 4.1.1.1)	Generator output is affected Pump output flows are affected Improper operation of relays may provoke spurious trip of equipment All magnetic circuits (transformers, generator, electric motors) are affected by overexcitation	Grid characteristics must permit operation of turbogenerator set in accordance with its operating limitations (see Figs 2 and 4) Below a predetermined under-frequency value, the pump motors must be disconnected and nominal power operation reduced to appropriate safe power levels If the NPP is not to regulate load, its droop setting can be adjusted so that frequency control and other regulation duties are reserved to other generating units whose droop must be set accordingly (see 4.3.1.2)
Rise in frequency (see 4.1.1.2)	Overpressure in primary coolant system	Overfrequency is regulated by reducing generation
Prolonged off-nominal frequency conditions (see 4.1.1.3)	High vibrations at resonance speed may induce failures in low-pressure turbine blades Limitations in generator capabilities Magnetic circuits in generator, transformers, electric motors may all be overexcited, leading to overheating	Turbine must be tripped according to manufacturer's specifications (see Fig.5); the equipment must be protected by relays with appropriate time delays The grid must possess the capability of improving its degraded frequency conditions by appropriate load-shedding and islanding schemes and reinforced interconnection for peak power availability (see 4.3.2)

TABLE I (cont.)

Event	Consequences	Remarks
Drop in voltage (see 4.1.2.1)	Retardation of pump motors System power oscillations In severe short-circuit conditions, torsional stresses may induce fatigue in the shaft of the turbogenerator set	Equipment must be disconnected on predetermined values of voltage and time Grid protection system must ensure an adequately fast fault clearance time Introduction of a power plant disconnect relay should be considered in the protective equipment of the turbogenerator set if the grid protection system has low performance

TABLE II. SUMMARY OF NPP/GRID INTERACTION

Event	Consequences	Remarks
Rise in voltage (see 4.1.2.2)	Damage to equipment, particularly that sensitive to overexcitation	Equipment must be disconnected from the grid on predetermined values of overvoltage and time
Prolonged off-nominal voltage conditions (see 4.1.2.3)	Difficulty in starting of large-capacity motors if the voltage is persistently low Instability of generator if the voltage is persistently high	Transformers could be provided with on-load tap-changing facilities Voltage regulating equipment should be installed in critical points of the grid (see 4.3.2.8) The possibilities of increasing the generator capability to accept higher values of leading Mvar should be discussed with the supplier

how to optimize solutions. To conduct this analysis, load studies and analyses of the system generation control and load restoration schemes should be performed, for which excitation characteristics, load governor characteristics and time constants, among other data, should be known for all the generating units of the system. While these data are generally readily available from suppliers in the case of modern power plants, including NPPs, special tests and measurements may be required in the case of old units for which the relevant characteristics may no longer be available from manufacturers. Basically, the results of this power system analysis and monitoring should include adequate information with respect to

- grid voltage and frequency fluctuations during NPP start-up and shut-down
- availability and reliability of the grid power supply at connecting points of the future NPP to the grid
- variations in power demand from the NPP, as expressed in power levels and rate of power changes required by the system.

Having obtained this information, the utility must take the following steps:

- Identification of those operational characteristics which would be feasible to be introduced in the selected NPP design in order to make it compatible with the operating requirements prevailing in the system
- Setting up of adequate reinforcement in the supply and transmission system which would be feasible to be introduced in order to accommodate NPP requirements
- Establishment of appropriate operating strategies of the other units to ensure system stability during NPP down-times.

In taking these steps, it is advisable to discuss at an early stage any unusual problem with potential suppliers since they may have alternatives which could mitigate the problems.

2.4. Conclusions

Table I presents the logic of action development which leads to the identification of the system characteristics; Table II summarizes the NPP/grid interactions and indicates possible actions to mitigate the consequences of the grid-induced events on the NPP. Reference is made to specific points in the text where relevant information can be found. Viable solutions should always be selected on a cost/benefit assessment.

3. CHARACTERISTIC FEATURES OF NUCLEAR POWER PLANTS

3.1. Types of nuclear power plants

Proven NPP designs which are at present available for export can be broadly divided into two categories

- NPPs with an off-load refuelling system (PWR, BWR)
- NPPs with an on-load refuelling system (PHWR)

3.1.1. Reactors with off-load refuelling system

Light-water reactors use enriched uranium and have enough built-in excess reactivity to enable full-capacity operation for a period varying from 12 to 18 months without refuelling. This means that the reactor needs to be shut down at such time intervals for refuelling (depending upon the load factor and the fuel and core design), for a period varying between 4 and 8 weeks (refuelling outage). Preventive maintenance and in-service inspection are also done during the refuelling outage and generally may extend the plant down-time beyond the actual refuelling time.

This requires the power system to have enough reserves for backing up the system during the scheduled NPP down-time period every 12–18 months; also, there should be judicious planning for these scheduled down-time periods to coincide, where possible, with the seasonal off-peak periods.

After refuelling, the newly added fuel needs 'conditioning', which means gradual increase of power, at a low rate and under conditions as dictated by the fuel manufacturers, for a certain period of time before nominal power can be reached. This period may vary from a few days to about three weeks. Therefore, after each refuelling, the utility has to make provisions for extra capacity to be available during fuel conditioning because the NPP will not be operating at nominal load.

After a reactor trip, there is normally enough excess reactivity so that the reactor can be restarted without being 'poisoned out' owing to xenon transients. However, the ability of the reactor to return to normal operation without 'poisoning out' can become restricted towards the end of the fuel cycle because of depletion of excess reactivity.

Reactors with off-load refuelling systems are more suitable for quick load changes over a wide range of power levels.

The task of supplying the varying power needs of the grid ultimately falls on the reactor and its control systems.[2]

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[2] Reference is made to the Guidebook on Nuclear Power Plant Control and Instrumentation, which is to be published by the IAEA.

3.1.1.1. Pressurized water reactors (PWRs) have good load-follow characteristics, and the reactor is controlled through control rods, soluble boron and coolant temperature changes.

- The power-change requirements of the daily load cycling and power ramps of up to about 10% per minute are controlled via actuations of the control rods and by soluble boron. For NPPs with heavy regulations duty, coolant temperature control is also available. Coolant temperature changes can minimize the wear of the control rod mechanism and power distribution disturbances due to control rod movements.
- Fast load changes, including the utilization of spinning reserve, are handled mostly by control rods and, if necessary, by coolant temperature changes. Soluble boron effects are slowly acting. They can, however, be used to compensate for additional control rod actuations to restore the desired power distribution and to compensate for xenon transients.

3.1.1.2. Boiling Water Reactors (BWRs) perform load-follow operation through recirculation flow control, control-rod manoeuvring and reactor pressure control.

- Recirculation flow control: This reactor power control is used during steady-state operation and daily/weekly load-follow operation. In this case, a high rate-of-power change can be performed, provided that the NPP is operating in the upper power range.
- Control-rod manoeuvring: This control system is used for long-term reactivity control in order to compensate for the fuel burn-up and for power distribution control during plant start-up and total power range operation. It may also be prompted by requirements of daily/weekly load-follow operation and by power ramps of up to 10% of nominal power per minute when the recirculation flow is held at a constant low value.
- Pressure control: Pressure is normally regulated with the turbine throttle valves. An increased power demand signal directly increases the reactor output by means of the reactor power control. The subsequent rise in steam pressure is immediately compensated by opening of the throttle valves via the pressure controller. In this control mode, the turbine throttle valve position follows the reactor output (turbine-follow-reactor) and the steam stored in the dome is not consumed.

3.1.2. Reactors with on-load refuelling system

Natural uranium reactors such as PHWRs do not have enough built-in excess reactivity and cannot operate for prolonged periods of time without refuelling, so an on-power fuelling system is provided. Fuelling is done almost daily and the unit is not required to be shut down. However, maintenance and inspection outages are still necessary, but the time of shut-down can be chosen at the best convenience of the operator and it is generally chosen at periods of low grid demand. These reactors must be restarted soon after a trip and brought to nominal power within one hour (if the turbine is hot). However, if they cannot be restarted within 30–45 minutes after a reactor trip (poison override time) and quickly loaded to 70% of the pre-trip power level, the built-up xenon overwhelms the excess reactivity and the reactor cannot be made critical until after 30–40 hours (poison outage time).

This limitation can be alleviated by using 'boosters', which provide for extra reactivity and can therefore favourably assist plant start-up and in-core fuel cycle extension. The advantage of a higher operational flexibility should, however, be weighed against the increased fuel cycle cost.

Because of the small excess reactivity of these reactors, their load-follow capability is limited to 30–40% of nominal power (i.e. 80–50% or 100–60%). The limitation is in bringing down the power below 67% because of xenon poisoning. The unit power regulation is obtained by adjusting the turbine load set-point to maintain the generator output at the level demanded by the local operator or by a generation control signal from a remote dispatching centre.

3.2. Operational modes of nuclear power plants

Although economic considerations would indicate constant load operation to be the operator's first choice, other reasons may require some operational flexibility and consequently justify some load-change capabilities of NPPs.

Nuclear power plants can be divided into three categories, depending upon their degree of ability to follow the load:

- *Constant-load plants.* These plants normally operate at nominal load. Start-up, shut-down and load changes are very infrequent, usually dictated by NPP requirements such as refuelling, inspections and internal restrictions.
- *Scheduled load-follow plants.* These plants normally operate at constant load, but may at certain predetermined times and during predetermined time intervals operate at partial load, according to grid requirements. These plants can follow predetermined loading/unloading patterns, i.e. 12–3–6–3 (100–50% nominal power), which means that the plant will operate at 100% for 12 hours, then power generation is reduced to 50% within three hours, followed by operation at this power level for six hours, and then power generation is increased to 100% within three hours.
- *Arbitrary load-follow plants.* These plants are expected to meet the grid load requirements, including fast changes of up to 10% per minute, at any time (in the upper power range).

3.2.1. Constant-load plants

The constant-load plants have the following advantages and disadvantages from the point of view of the designer and the operator:

Advantages:

- Lower generation cost than for load-follow plants
- The plant design may be basically simpler, since the thermal stresses in materials/components are expected to be less and hence the unit may cost less
- To some extent, instrumentation and control may be less extensive and/or sophisticated (reactor start-up can be manual/semi-automatic, leaving only some regulation and protection to be done by automatic devices)
- The unit storage capacity (i.e. steam storage, poison addition tanks, etc.) may be less extensive.

Disadvantages:

- The NPP is expected to operate at constant load and is not amenable to load change
- The plant has long start-up/shut-down times and has difficulty to come easily to house-load or partial-load operation
- The load-change requirements of the grid are to be met by the other generating units of the system and this may require extensive backfitting (drop setting, control system adjustment, etc.) (see 4.3.1.2).

3.2.2. Scheduled and arbitrary load-follow plants

The scheduled and arbitrary load-follow plants have the following advantages and disadvantages:

Advantages

- Shorter start-up time than constant-load plants; ability to change plant output on predetermined schedule
- Quick loading/unloading capabilities help meet the grid load-change requirements
- Ability to come to partial-load operation and house-load operation with relative ease
- Operation on automatic frequency control mode is possible.

Disadvantages

- Higher generation cost than for constant-load plants
- Plant components are exposed to a large number of thermal stress cycles and may have to be designed accordingly, and hence will be more expensive
- The number of fuel failures may be greater if precautions are not taken

– The amount and degree of sophistication in instrumentation and control is increased; however, a cost/benefit assessment will generally reveal that this is acceptable, considering the advantages of higher operational flexibility.

3.3. Quality of electric power supply

3.3.1. External grid power supply

Safe start-up, running and shut-down of NPPs require adequate characteristics of the external grid power supply, since it should be possible to supply the electric power system (EPS) of the NPP with electric power from the main electric generator and from the transmission grid. In the case of loss of power from the generator under operational or accident conditions the EPS should be supplied by the grid. When determining reliability criteria for reactor safety, the probability of a certain number of grid power failures per year is assumed. If, however, the number of grid power failures per year is higher, the reliability criteria will be adversely affected.

In a low-performance system, the higher probability of grid power failure at connecting points of the NPP to the grid may necessitate the provision of more than one line from the NPP to the grid, each having a different geographical route, in order to avoid common-cause failures. Similarly, when the reliability of the off-site power supply is relatively low, the reliability of the on-site power supply shall be such that a high overall reliability is achieved. In a low-performance system, the on-site power supply and its emergency systems may have to be compensated by adequate redundancy so that the overall reliability criteria are met. More frequent testing of the emergency EPS may also be necessary.

This subject is covered extensively in the IAEA Safety Guide No. 50-SG-D7 (NUSS programme) on Emergency Power System at Nuclear Power Plants, to which reference is made for specific information.

3.3.2. Power supplies for station services

The power supplies for station services of NPPs are divided into four classes, according to their levels of reliability requirement, ranging from power which can be interrupted, with limited and acceptable consequences, to uninterruptible power.

Class-IV power supply

Power to auxiliaries and equipment which can tolerate long interruptions without danger to personnel and station equipment is obtained from Class-IV power supply. Complete loss of Class-IV power will initiate a reactor shut-down.

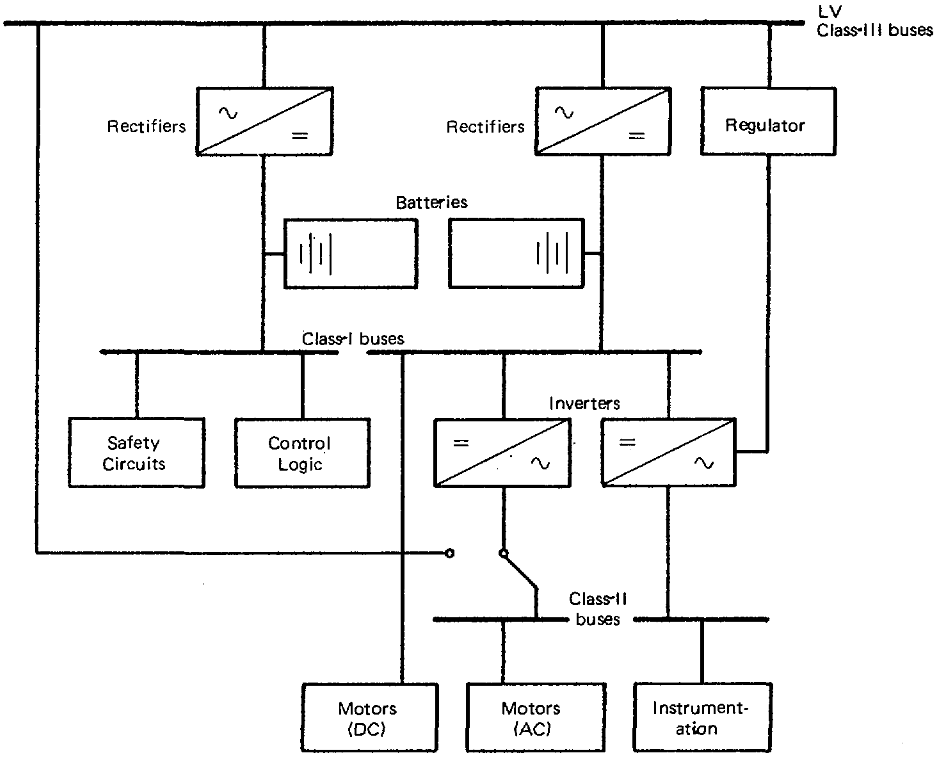

FIG. 3. Low-voltage AC/DC power supply free from grid disturbances.

Class-III power supply

Alternating current (AC) power supply to auxiliaries which are necessary for the safe shut-down of the reactor and turbine is obtained from Class-III power supply with stand-by diesel generator back-up. These auxiliaries can tolerate short interruptions in their power supplies. (The total interruption time may be limited to three minutes with the stand-by generators which can be up to speed and ready to accept load in less than two minutes.)

Class-II power supply (see Fig.3)

Uninterruptible alternating current (AC) power supply for essential auxiliaries is obtained from Class-II power supply. This comprises:

(a) Redundant low-voltage AC three-phase buses, which supply critical motor loads (i.e. emergency lighting). Each of these buses is supplied through an inverter from a Class-III bus via a rectifier in parallel with a battery. (Under normal operation, Class-II supply comes from Class-IV supply.)

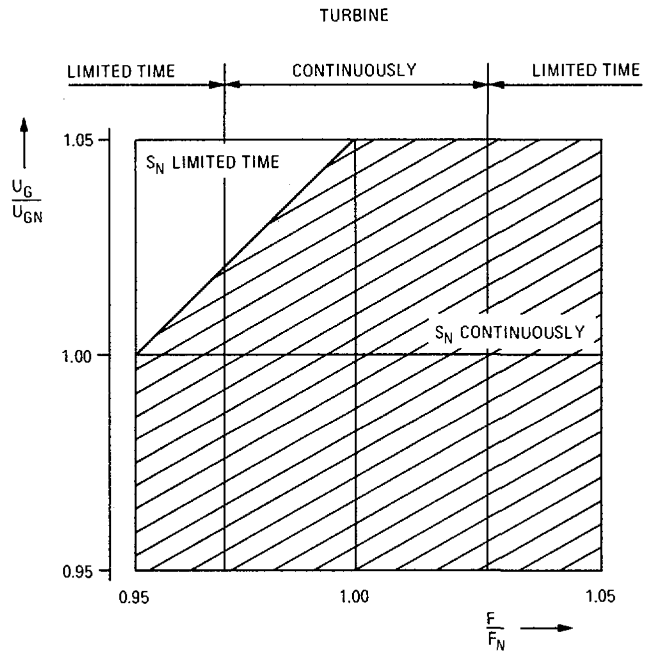

FIG.4. Typical loading diagram of a unit during voltage and frequency variations, valid for nominal values of voltage and frequency. S_N *= nominal apparent power,* U_G *= generator voltage,* U_{GN} *= generator nominal voltage,* F *= frequency,* F_N *= nominal frequency.*

(b) Redundant low-voltage AC single-phase buses, which supply AC instrument loads and the station computers. These buses are fed through an inverter from Class-I buses which are fed from Class-III buses via rectifiers in parallel with batteries. In the event of an inverter failure, power is supplied directly to the applicable low-voltage bus and through a voltage regulator to the applicable instrument bus. If disruption or loss of Class-III power occurs, the battery in the applicable circuit will provide the necessary power without interruption.

Class-I power supply (see Fig.3)

Uninterruptible direct current (DC) power supply for essential auxiliaries is obtained from Class-I power supply. This comprises:

(a) Redundant independent DC instrument buses, each supplying power to the control logic circuits and reactor safety circuits in parallel with Class-IV supply. Each of these buses is supplied from a Class-III bus via a rectifier in parallel with a battery.

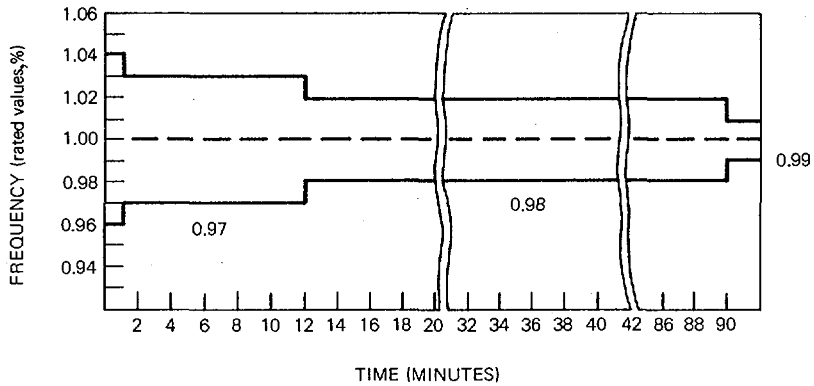

FIG.5. Recommendations of a turbine manufacturer (General Electric Co., New York) for permissible off-nominal frequency full-load operation of large turbines.

- *A reduction in frequency of 1% (0.99 rated value) would not have any effect on bucket life*
- *A reduction in frequency of 2% (0.98 rated value) for more than 90 minutes could result in damage*
- *A reduction in frequency of 3% (0.97 rated value) for more than 10–15 minutes could result in damage*
- *A reduction in frequency of 4% (0.96 rated value) for more than 1 minute could result in damage.*

(b) Redundant DC power buses which provide power for DC motors, switchgear operation and for the Class-II AC buses via inverters. These DC buses are supplied from Class-III buses via a rectifier in parallel with batteries.

3.3.3. Voltage and frequency deviation of the external grid

Off-nominal voltage and frequency conditions of the grid affect the operation of the turbogenerator. The prospective owner of the NPP should request the supplier to submit the load diagram of the turbine during voltage/frequency deviations (Fig.4) and the generator output diagram (Fig.2), and their limitations with regard to the expected functional requirements of the grid should be verified. The most frequently recurring deviations from nominal values of the grid characteristics must be within the operating limits of the turbogenerating set as specified by the supplier of the equipment (see also Fig.5).

3.3.3.1. Changes in voltage

The NPP power supply for instrumentation and control, including their protection systems, must be made immune from grid voltage and frequency deviations. This can be achieved with any rectifier-supplied, battery-backed low-voltage redundant system, as shown in Fig.3.

Frequency changes do not affect this power supply. Different limitations apply to the permitted voltage deviations of the power supply to the plant electric equipment during start-up and normal operation.

Critical problem areas in running NPPs outside the prescribed limits of voltage include: (a) start-up of motors, (b) power level and torque of motors, (c) pump flow, (d) valve drives, and (e) setting of operating limits of relays.

The permitted deviations in standardized design may differ from one supplier to another and must be carefully verified by the prospective owner of the NPP with regard to the currently prevailing conditions of his grid.

Typical supplier-guaranteed limits for correct operation at start-up conditions may include:

- high-voltage motors: down to 75% of nominal voltage
- low-voltage motors: down to 70% of nominal voltage
- valve drives: down to 80% of nominal voltage.

The prospective owner of the NPP should also clarify whether such limits include the overall performance of the aggregate (motor and pump).

Short-time voltage drops as reported above can be tolerated if high-capacity motors are started. For bus bars of diesel back-up generators, a drop of 15–20% is generally acceptable. However, continuous operation of large-capacity fully loaded motors at such levels is not recommended. Off-nominal voltage conditions of prolonged duration can be compensated by on-load tap changers; usually, these compensate for the following deviations from nominal values:

± 10% for normal transformers

± 15% for stand-by grid transformers.

If larger deviations are expected, the capability of the turbogenerator will have to be discussed with the equipment manufacturer and guaranteed by him.

3.3.3.2. Changes in frequency

Nuclear power plants of standardized design can normally operate with grid frequency deviations which are expected to remain within 1% of the rated frequency. Deviations of up to 5% of the rated frequency may be permitted for short times (see Fig.5). Under these conditions, restrictions in NPP operation automatically initiate a power run-back (see Section 3.4.3) via a special limit control system. When the frequency drops to below 5% of the rated frequency, the turbine must be tripped if the system cannot be islanded (see Section 4.1.1.3) and the reactor power brought down to a safe level. Beyond 7% of the rated frequency, the reactor will be scrammed (93% of coolant pump rated speed – see Section 4.1.1.1). Availability of reactor set-back capability is an important feature which enables the reactor, during frequency variations, to maintain its output and to come back to nominal power quickly after the disturbance has been cleared.

3.4. Operational characteristics of nuclear power plants

The design of a NPP has its own characteristic operating features. The manufacturer of the equipment should be requested to clearly display the basic design features of the plant to be supplied in order to identify improvements necessary to strengthen the grid performance for safe operation of the NPP. This is even more important when the plant is the first nuclear unit and likely the largest one in the system.

During its operational life, the NPP must serve the load-change requirements of the grid and must therefore be able to feature adequate operating performance. In a low-performance grid, the ability of the NPP to pick up load within a short time may be of particular relevance. The time necessary to reach nominal power from zero power primarily depends on the temperature level in the NSSS and BOP. This time also depends on the NPP type and design and may thus vary from one manufacturer to another. In this respect and in the interest of the NPP owner, it is important that the start-up time be guaranteed by the equipment supplier and adequately demonstrated by documented operating experience of an existing NPP of the same size and type as the envisaged NPP.

The start-up of a NPP basically comprises the following major steps:

- Warm-up of primary and secondary systems from cold conditions (low pressure, low temperature) to warm conditions. This operation is necessary after a prolonged down-time of the plant (refuelling and/or maintenance).
- Start-up from warm (no power) to low-power-range conditions. This operation is required when the plant re-starts soon after a reactor trip or plant shut-down to zero reactor power. The power level is brought to a minimum value, from which quick plant loading in the power range is possible.
- Load pick-up in the power range. This operation is performed when loading the plant to nominal power and during any period of scheduled load-follow operation.

To respond to the load requirements during operation in the power range, the plant may have to perform rapid power changes of limited magnitude (step power changes) and/or slow power changes of large magnitude (ramp power changes). Normally, a power change of limited magnitude can be performed with a high gradient, and a large power change can be performed with a low gradient. Moreover, the permissible gradient depends also on the power range at which the power change is performed. The following example will assist in clarifying these points.

- Step power changes at a rate of 1% of nominal power per second may be permitted in the range of up to 10% of nominal power (i.e. from 90% to 100% of nominal power: frequency control band), with the restriction that, after a step larger than ± 5%, a dead-time of a few minutes must elapse before the next step, to permit the power control to take action.

– Ramp power changes can be performed with different rates of power change, depending on the power range at which they are performed. Therefore, 2% per minute over a range of 80% of nominal power, 5% per minute over a range of 50% of nominal power, and 10% per minute over a range of 20% of nominal power are generally permitted.

3.4.1. Start-up from cold reactor and cold turbine to nominal power operation

This operation takes a relatively long time and is necessary after every prolonged shut-down of the NPP. The guaranteed start-up time for commercial NPPs from cold conditions to 100% of nominal power may be up to 25 hours and even longer (for constant-load plants). The corresponding time for a fossil-fuelled power plant is 2–5 hours.

For LWRs, after each refuelling outage, 'conditioning' of the new fuel is needed, which takes up to three weeks (depending on the fuel/NPP manufacturer), during which the reactor power is raised at a slow rate to nominal power (see Section 3.5.1). Once the fuel is 'conditioned', using the method recommended by the fuel/reactor manufacturer, subsequent start-ups from cold conditions can be performed in the time range mentioned above. During start-up, the NPP needs reliable power supply from the grid to the amount of 5–7% of the rated unit output at stabilized voltage and frequency conditions.

3.4.2. Start-up from hot reactor and hot turbine to nominal power operation

If the NPP has tripped and is in a position to be re-started, this should be done in the shortest possible time, while the reactor and the turbine systems are hot. For LWRs, this takes 1–3 hours, depending on the plant I&C design and its degree of automation. PHWRs must be brought to 70% of the pre-trip power level within 30–45 minutes, in order to avoid poison outage after a trip. The corresponding time for a fossil-fuelled power plant is 1–3 hours. If the plant is re-started after a period during which the reactor has been kept at hot stand-by but the turbine has cooled down, a more cautious start-up has to be performed since the limitations imposed by the manufacturer on the BOP have to be observed; it may take about 7–16 hours to raise the plant output to 100% of nominal power, depending on the amount of turbine cool-down. Controlled shut-down of the reactor from 100% power or below to subcritical conditions (hot stand-by) can be carried out within a few seconds to up to 2 hours, depending on plant design. During shut-down times of short duration, the reactor is kept hot in order to enable quick plant re-start.

3.4.3. Reactor power set-back capabilities

There are several reasons why NPPs may have to resort to run-back to partial load ratings. These reasons may be external (originating in the grid) or internal (as a consequence of equipment malfunction in NPPs).

3.4.3.1. External reasons for NPP set-back operation

Nuclear power plants may resort to a quick run-back to partial power output because of some grid-induced critical event. Such events are listed below.

- Large load drop in the grid as a consequence of upset system conditions leading to system islanding. The NPP may be required to run back to 80%–60% of nominal load in order to meet the balance between the generation and the load in the islanded system. The rate-of-power changes and the maximum values for step load shedding depend on NPP design characteristics, load requirements and characteristics of other generating units in the islanded system, and must be taken fully into account when the islanding scheme is engineered.
- Isolation of the NPP from the grid, with the NPP only serving reduced local loads. The NPP may be required to run back to 40% or less of nominal power in order to avoid a trip and to maintain generation. The minimum design steam flow to the turbine will govern the minimum acceptable power level.
- Severe disturbance, such as grid power failure. The NPP may be required to cut off all external ties, to run back to supply its own house load, and to be ready to accept load again up to nominal power soon after the disturbance has been cleared. During house-load operation, only about 5% of nominal power is generated by the generator while the reactor power is maintained at a higher level. When the disturbance is a grid-induced event, the reactor can be operated at up to 30% of nominal power if automatic control is preferred (MILAC), or even at a higher power level (MILQUICK) for quick return to power if the disturbance is anticipated to be of short duration (see Section 3.4.3.3).

In the house-load condition, it should be possible to operate a unit having a unit-bound auxiliary system supply for several hours at rated speed, with the unit only supplying its own auxiliary systems. The voltage regulator must ensure that the voltage of the isolated auxiliary supply system remains within the permissible limits. During house-load operation, the NPP is able to synchronize with its own means and to be quickly reloaded to nominal power. These operating features enable the NPP to be independent from the grid and to keep the main pumps running (normally, the emergency electric power system with diesel set does not enable the start-up of the large primary coolant pumps and the boiler feedwater pumps).

3.4.3.2. Internal reasons for NPP set-back operation

Nuclear power plants may be requested to resort to intermediate safe power levels because of malfunctioning of internal plant systems and/or components; this includes:

- trip of one of the subsystems, such as reactor cooling, feedwater, condensate, condenser cooling (as permitted by licensing regulations)
- component failure or overheating
- control malfunctioning.

For each case, a distinctly defined active measure is provided (sequence or redundant limit controls) by the relevant system design, including run-back to acceptable operating conditions. The operator must closely monitor the number of such occurrences and the different levels at which the reactor power has been set back, because these operational modes erode part of the plant life endurance and their cumulative effects during the plant life must not exceed those assumed in plant design (see Section 3.5.3) or else the guaranteed life of the plant will be shortened.

3.4.3.3. Minimum load with automatic control (MILAC) and minimum load for quick return (MILQUICK)

MILAC is defined as the minimum load value at which the plant can be operated without manual control. Values of between 15 and 30% of nominal power are possible for modern LWRs, depending mainly on turbine design and reactor control stability.

In MILQUICK conditions, the reactor is kept at its highest possible power levels, depending upon condenser by-pass capacity, whereas the generator is run at a low power level. This performance is requested when, after disconnection of the NPP from the supply system, the load dispatching centre anticipates that the fault is of short duration, and plant re-synchronization to the grid and a quick loading signal are expected within a short time. Under these conditions the turbine could possibly be returned to full load very quickly, depending on the amount of cool-down that has occurred. If the turbine has cooled down, quick return to load is not permitted because of thermal limitations in the turbine (see Section 3.5.3).

During operation at intermediate reactor power levels while the generator produces the house load, the excess steam is dumped to the steam dump condenser or to the atmosphere if this is permitted by licensing regulations and if adequate supply of demineralized water is available.

In selecting the NPP load rejection capacity, utmost care must be exercised in appraising the economy of a more flexible operating performance against the design extra-cost this may imply. In this respect, it must be considered that load rejection capacity may be designed for conditions such as:

- approximately 80% of the rated main steam flow for a high steam-dumping capacity without any set-back functions
- approximately 50% of the rated main steam flow for a moderate steam-dumping capacity with a set-back function to, say, 60% of nominal power in about 10 to 20 seconds.

Set-back capabilities to lower power levels are also possible, even to full load rejection. However, it must be considered that, if dumping steam to the atmosphere is not permitted, then dispatching the steam to a special dump condenser may involve:

- additional cost of the equipment
- additional design complexity
- additional material stress problems
- additional cost for redundancy to ensure reliable functions.

For PHWRs, a large steam by-pass capacity is more advantageous. Steam dumping provides PHWRs with good capabilities for quick return to full power soon after a turbine trip.

If the low-power operation periods are of short duration, it may be advantageous for these plants to dump steam to the condenser or to the atmosphere during the entire period and to keep the plant running at high reactor power level. While this appears to be wasting energy, the cost of this energy loss must be balanced against the cost of providing continuous excess reactivity in the core to permit load-follow operation.

3.5. Limitations of load-change capabilities of nuclear power plants

If the NPP is called upon to perform load-follow operation, its ability of changing the output to meet the system load-change requirements depends upon:

- plant design characteristics
- past operational plant history
- magnitude of the load change required
- rate of the load change required
- plant power level at which the load change is performed.

Operating experience of NPPs in the load-follow mode is available, but for economic reasons these plants are used today primarily for base load. However, the inclusion of load-follow capabilities in the guaranteed operating performance is regarded at present to be an important requirement of modern NPP design. Such load-follow capabilities are, however, subject to certain limitations imposed by the equipment manufacturers.

3.5.1. Restrictions in output changes due to fuel performance

In the past, some of the fuel failures associated with load cycling operation of NPPs were due to insufficient knowledge of designers, manufacturers and operators regarding fuel performance. Faults were mainly due to the stresses induced by operators' actions which were permitted because of lack of proper understanding of pellet/clad interactions. According to present knowledge, fuel failures depend upon:

- fuel design
- process of manufacture
- water chemistry
- control strategy
- mode of operation.

As operating experience has accumulated and better understanding of fuel behaviour has been achieved, more confidence is acquired in the operating performance of modern well-designed fuel elements featuring daily or weekly load cycling in a manner approved by the fuel manufacturer and ensured by an established and well-proven control strategy. Fuel failure may develop because of combinations of all of the following occurrences:

- After refuelling, the local power density in the fuel is raised too quickly from low to high values
- The fuel has previously been kept for a long period (weeks) at low power density
- The local power density is raised above a certain 'conditioning' level which depends upon the fuel burn-up. (For some fuel designs this may be from above 600 W/cm for fresh fuel to 350 W/cm for fuel with high burn-up.)

To avoid the above-mentioned causes of fuel failure, 'conditioning' of the fresh fuel after each refuelling (in LWRs) may be requested for guaranteed fuel performance. For conditioning the fuel, the rate of power increase soon after reactor re-start following each refuelling is limited to approximately 0.5–2% of nominal power per hour. Therefore, for a period of three days to about three weeks, nominal power will not be available from the NPP. Consequently, the load dispatcher should make suitable provision to cater for the load requirements of the system during these restrictions of NPP generation by means of adequate loading strategies for the other generating units of the system.

Fuel failure which may be provoked by the first ramp of a non-conditioned fuel can be avoided if:

- start-up after refuelling is performed slowly
- quick ramps after long periods of partial load operation are avoided
- large changes in fuel power density distribution are avoided.

If the NPP is required to change its power output quickly, the decision regarding permissible local power distribution becomes complex and is beyond the capability of a manually operated control system; it may then become necessary to use a redundant, automatic, computer-assisted control system.

3.5.2. Restrictions in output changes due to reactivity limitations

For maintaining constant reactor power, a reactivity balance must be kept. For increasing the power level, it is necessary to add positive reactivity, and for lowering the power level, negative reactivity must be added.

In some conditions, however, the power rise may be limited because of the inability to insert positive reactivity as required, since all absorber rods in the reactor control system are withdrawn and no other reactivity control means are available; the reasons for this are:

- control elements cannot be withdrawn because operating limits such as high local power density are reached
- all reactivity changes by control elements and other means are needed for transient xenon poisoning
- storage tanks of liquid control means (boric acid) are full because of control actions in previous load changes.

Limitations in excess reactivity do not have any destructive or harmful effect on the NPP but decrease the operational flexibility and sometimes may even lead to subcritical reactor conditions if xenon poisoning effects cannot be overcome.

3.5.3. Restrictions in output changes due to thermal stresses in materials

Thermal stresses in materials are dependent on the range and rate of power changes and, since the effects are cumulative, the total number of power cyclings performed during the lifetime of components.

Such stresses may initiate damages in critical points of the NPP. Some of these damages have been identified by NPP designers to be generally located in:

- pipe walls
- thick walls of components
- nozzles of large components and adjacent areas
- tanks of small mass-to-flow ratio
- points of large temperature changes
- welded joints of dissimilar materials.

The extent of these damages depends mainly upon
- magnitude of pressure and temperature changes
- rate of temperature and pressure changes
- number of cycles
- massiveness of the parts involved.

Manufacturers have calculated for given plant loading/unloading patterns the impact of the associated thermal stresses and their consequences on the guaranteed life of the plant components. For example, typical assumptions as used by designers in their thermal stress evaluation analysis may include the following data:

- Rapid changes (step-wise) of ± 10% of rated power, to be performed once a day, i.e. 15 000 times during an assumed NPP lifetime of 40 years
- Rapid changes of ± 5% of rated power, to be performed ten times per day, i.e. 150 000 times during a NPP lifetime of 40 years
- In the case of ramp changes of a certain magnitude and power range, the following assumptions may be made:

Power range (%)	Rate of change (%/min)	Frequency of occurrences	Number of occurrences during NPP lifetime
100–80–100	10	5 per day	75 000
100–60–100	5	1 per day	15 000
100–40–100	5	5 per month	2 500
100–20–100	2	5 per month	2 500
100– 0–100	2	1 per month	500

Such data are used for thermal stress calculations in selected components. These assumptions are determined by the expected operational plant requirements, but should be more stringent in order to provide for adequate margins. However, it should be kept in mind that overdesign may be highly expensive and sometimes even lead to counteracting effects. Additional assumptions should be contemplated for equipment trips due to power supply transients and other unexpected events which may be frequent in a low-performance grid.

The prospective NPP owner should carefully review all these assumptions to determine whether they do correspond to his functional requirements; he may also request the manufacturer to investigate the consequences of different assumptions if his system has requirements different from those assumed and guaranteed for standardized design.

Turbine manufacturers specify two different types of stresses which may induce failures:

(a) *Mechanical stresses.* These depend upon the magnitude and frequency of mechanical vibrations. Most common are strong vibrations due to resonant speed of the turbine which may induce failures in the low-pressure turbine blades (see Section 4.1.1.3). Recent investigations of the dynamic behaviour of large turbogenerator sets have shown that also torsional vibrations induced by short circuits of long duration in the vicinity of the power plant can induce shaft fatigue and reduce the effective life of the unit.[3]

(b) *Thermal stresses* in materials associated with plant start-up and load-change operation (a case in point is the differential heating of the turbine casing which must be appraised since too rapid admission of steam may pose problems). These stresses, depending on load change, rate of change and cumulative number of occurrences, affect the life of the turbine. Of course, the problem of thermal stresses in materials also exists in other plant components. If different suppliers have been chosen, the prospective owner should verify that the assumptions made for the NSSS are consistent with those made for the BOP.

The results of a turbine stress analysis as performed by a manufacturer for the assumptions indicated are listed below.

Load change (%)	Rate of change (%/min)	Number of occurrences	Turbine lifetime consumed (%)
100–80–100	10	10^5	1
100–60–100	10	1.5×10^4	16
100–40–100	5	1.2×10^4	80
100–20–100	5	1000	10
100– 0–100	5–2	400	4
Start-up (cold)/ shut-down	As permitted, only by start-up/shut-down control devices	200	6
		Total	> 100%

[3] It has been found that, even in the case of a three-phase fault, the torsional stress has no effect if the fault is cleared within 150 ms. Stressing of the stator winding is also low in such cases. This calls for quick-acting grid protection equipment. In a low-performance grid, this requirement may not be satisfied, so that fault clearing times in excess of 150 ms as well as fault clearance in the second step of grid protection (i.e. as a consequence of a circuit breaker malfunction) are often encountered. In these cases, the only effective measure for avoiding high torsional stresses is to disconnect the turbogenerator set from the grid. Immediate re-synchronization can then be effected. The necessary protective equipment for this purpose is a power plant disconnect relay.

The results show that, in this case, the combined effects of all assumed thermal stresses may shorten the life of the turbine compared with the plant lifetime and that the cycle 100–40–100 is the most critical. Therefore, the following points should be considered:

– It may become imperative to change the assumptions and to take these changes into account in operating practice so that the turbine life consumed by thermal stresses remains below 100% during the expected lifetime of the plant.
– The design may need modifications in order to ensure the ability of the turbine to withstand all thermal stresses induced by the assumed mode of operation.

In any case, techniques of failure prediction (ultrasonic tests, radiography, etc.) for pre-warning the operator should be incorporated in the design and strictly monitored by the operator.

It is important that the final judgement regarding the ability of the envisaged NPP to perform load-follow operation be based on the results of theoretical calculations and also that the manufacturer be in a position to guarantee the design characteristics on the basis of actual operating experience from an existing NPP of the same type and in the same size range.

4. INTERACTION OF GRID AND NUCLEAR POWER PLANT

4.1. Influence of the grid on the nuclear power plant

Transients originating in the grid lead to transients in the NPP in a chain-like fashion, the effect of which, depending upon the severity of the disturbance, may lead to islanding of the NPP or even to tripping of the reactor. Such disturbances adversely affect the performance and life of the plant. The performance of the NPP (availability, life, increased maintenance effort) is affected by the frequent grid disturbances prevalent in low-performance systems as well as by the increased incidence of emergency situations arising therefrom, and in this context a study of the dynamic interaction between grid and NPP becomes extremely important.

Careful evaluations should lead to a concept of the proper NPP design, the possible addition of equipment and those system operation strategies which will most economically ensure the safe operation of the NPP.

In a low-performance system, improvements of grid characteristics are generally necessary. If it is not technically possible or economically viable to compensate for all grid deficiencies, the conclusion may quite simply be that the system just cannot support the operation of a NPP.

4.1.1. Effects of frequency change on NPP operation

The frequency in a grid can change quickly or slowly. It can persist at off-nominal conditions or it can come back to a nominal value after a sharp change. If the frequency has fallen because of a loss of generation, the grid can still recover if there is adequate spinning reserve. If spinning reserve is not adequate, remedial measures like load shedding and/or system islanding have to be resorted to in order to improve the frequency. Basically, any change in frequency affects NPP operation through the speed governor of the turbogenerator and through a change in the speed of pumps delivering flows to the reactor and secondary coolant circuits.

4.1.1.1. Sharp drop in frequency

When the frequency drops, the turbogenerator assumes load, depending upon the load governor droop setting and the frequency deviation. The resulting mismatch of reactor power produced and power drawn from the reactor causes an intervention of the control system. Coolant circulation pump motors are also affected. On a drop in frequency, the output flow of the pumps will come down as the developed head is proportional to the square of the speed/frequency, and the process system may be disturbed in PWRs by a change in primary coolant average temperature, in BWRs by void distribution, and in PHWRs by change of reactor delta T. Measurements of reactor power may be affected if they are not supervised by flow signals. In some PHWR designs, large-capacity pump motors are provided with high-inertia flywheels to improve the coast-down time of the pumps in accident conditions and are protected by under-power relays. On a sharp drop in frequency – although the drop may be of small magnitude – the motor may change from the induction motor mode to the induction generator mode and come back to the induction motor mode, which may result in operation of the under-power relays and a consequent spurious reactor trip. In this case, the operation of under-power relays should be interlocked with under-frequency relays set at predetermined frequency values. If the frequency drop does not go below the setting value, the under-power relays will not trip the pump and hence no spurious reactor trip will take place.

In some LWR designs the use of under-power relays is not contemplated, but the reactor will be scrammed if the speed of the main coolant pumps drops below 93% of its rated value (see Section 3.3.3.2).

If the drop in frequency is accompanied by a large change of reactive power inducing overvoltage conditions, the overexcitation relays intended for protection of generators and transformers may operate. In the case of overexcitation, the transformers may be more affected since they are normally designed to operate approximately at the knee-point of their magnetic saturation characteristic at nominal voltage.[4]

4.1.1.2. Sharp rise in frequency

Tripping of a tie line disconnects some load from the grid and the grid frequency suddenly rises. Because of the frequency rise, the turbine speed governor closes the throttle valves which reduce the power in the turbine; with the reactor power level unchanged, it is now greater than that drawn by the turbine. The mismatch causes transient overpressure in BWRs, and overtemperature and overpressure in PWRs. Excess steam is dumped to the reject condenser or to the atmosphere, if permitted, and the reactor power is brought to the level of turbine demand by the intervention of the control system.

Pumps develop more head and hence the increased flows affect the feedwater control system and the primary pressure and temperature control. Thermal stresses may develop in critical components, following admittance of increased cold water inflow, unless appropriate over-frequency protection is provided. The introduction of over-frequency relays with an appropriate time delay to separate the NPP from the grid helps to avoid possible damage to the equipment in persistent over-frequency conditions. Moderate over-frequency conditions can generally be easily controlled by reducing generation and as such do not pose any problems. Automatically disconnecting the NPP from the grid may therefore be warranted only in severe conditions. Speed limiters are normally provided in the turbine control system to prevent turbine overspeed.

4.1.1.3. Prolonged off-nominal frequency conditions

In the case of insufficient generating capacity and inadequacy of the load-shedding schemes, the utility may be forced to operate at a frequency level lower than nominal over an extended period of time. Turbine manufacturers specify stringent limitations on off-nominal frequency operation of the turbines. Because of vast improvements in the materials and the construction of blades, the low-pressure turbine buckets are long and slender. The vibration stress level in the blades at rated speed is well below the endurance limit. However, at off-nominal frequency conditions, the blades may come within the domain of resonant speed at which unacceptably high vibration may develop, inducing

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[4] Modern power transformers are designed to operate at high flux densities which are near to the saturation value. Depending upon their thermal time constant, the power transformers have some overexcitation capacity. Flux – a measure of excitation – is conveniently expressed by the ratio of per-unit voltage to per-unit frequency. Hence, an increase of voltage or a reduction of frequency is a cause of over-fluxing. Suitable protection should be considered when large frequency and voltage deviations from nominal values are expected.

blade failures. Figure 5 shows the typical recommendations of a turbine manufacturer. It can be seen that modern turbines suitable for high-performance grids can operate only for a few minutes at a frequency below 100% of the rated value. Such operations have a cumulative effect and are permitted only for a certain total period over the life of the unit. Although designing the turbine to operate continuously within a more liberal frequency range without deleterious effects would be a significant advantage for operators of low-performance systems, such design modifications are difficult and often impractical to obtain since proven and guaranteed equipment manufacturing is standardized to a large extent. Therefore, upon frequency drop, the NPP must be disconnected from the grid at predetermined frequency values with graded time delays if in the meantime the system frequency has not recovered by virtue of islanding and/or load-shedding schemes. Similarly, large-capacity pump motors should be designed so as to be safely operated until certain low-frequency limits as specified by the manufacturers are reached. Beyond these limits, means should be provided to adequately protect these motors. Large-capacity motors with the capability of starting and running at frequency conditions beyond the standardized limits will require a special design which may prove very expensive, inefficient and with limited guaranteed reliability.

4.1.2. Effects of voltage change on NPP operation

Off-nominal voltage conditions at various points of the grid are mainly due to the following reasons:

- Inability of the grid protection system to quickly clear transmission line faults
- Long transmission lines without intermediate power stations
- Lack of voltage control equipment, such as synchronous condenser and static capacitors
- Absence of on-load tap-changing transformers
- Insufficient capacity of the transmission lines to carry the peak load.

Better grid voltage conditions are generally achieved by adequate voltage control equipment at critical points of the grid and by good meshing in the transmission network. Appropriate siting of the generating units is also effective in maintaining a good control of the grid voltage.

4.1.2.1. Sharp drop in voltage

A rapid drop in voltage (voltage dip) is mainly due to an electric fault on a transmission line(s). The extent of the dip depends upon the proximity and nature of the fault, and upon the sensitivity of the automatic voltage regulator

(AVR) equipment of the generators connected in the grid.[5] The duration of the dip depends on the speed of the protective relays and their co-ordination as well as on the circuit breaker characteristics and their speed of operation. During sharp voltage dip conditions, all connected motors will be retarded. The magnitude of the retardation is determined by the voltage dip and its duration, the characteristics of the load, and the mass moment of inertia of the motor-pump assembly.

To mitigate the consequences of a drop in voltage, the protection system of a low-performance grid should be studied and improved by:

- introducing fast-acting fault-detecting relays with good co-ordination
- introducing fast-acting breakers for quick isolation of faults
- introducing auto-reclose features on the breakers.[6]

4.1.2.2. Sharp rise in voltage

If the grid loses a large load and the NPP remains connected with long, lightly loaded lines at the remote end, the grid voltage may rise sharply. The effect of high voltage can be deleterious to equipment such as transformers and large-capacity motors which are sensitive to overexcitation. The electric generator may become unstable. Adequate overvoltage and overexcitation protection of the electric equipment should be available, as specified by current electrical standards.

4.1.2.3. Prolonged off-nominal voltage operation

When the voltage control equipment is inadequate, it may not be possible to maintain the same voltage at different points of the grid at all times, and poor voltage conditions may develop and persist over extended periods.

Prolonged high voltage on the grid may force the generator to accept large values of leading reactive power (Mvar) and it may become unstable. In certain cases, it may trip on overexcitation (see Fig.2). Prolonged low voltage on the grid may create problems in starting and running large-capacity motors of the NPP. Some motors are provided with flywheels and have a relatively long start-up time. If the voltage is too low, the starting torque may become

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[5] During power system disturbances, fast-responding voltage regulators can adversely affect the recovery of the system as they can cause an overvoltage condition. One method of limiting uncontrolled interaction between all generators on the grid including the NPP is to dampen the excitation response during a transient condition. Power system stabilizers are available in modern excitation systems for this purpose; however, these are known to induce undesirable oscillations and care must be exercised when they are adopted.

[6] Single-phase high-speed reclosure is particularly effective. Three-phase high-speed reclosure may cause problems of torsional stresses in the turbine shaft if the fault-clearing time of the grid protection system is too long (see Section 3.5.3).

insufficient and the motor may not come up to full speed and eventually trip on stall protection. If the pump motor is operating, it may trip on overload.[7] If during pump start-up the pump trips owing to overload, an immediate re-start is harmful to the pump motor. Sufficient time must be allowed between subsequent start-ups in order to allow for adequate cool-down of the pump motor.

4.2. Influence of the nuclear power plant on the grid

Because of its relatively large size the NPP, while operating, plays an important role in stabilizing a low-performance grid. In addition, NPPs have characteristics which permit a relatively high rate of power change when operating at reduced power in the upper power range. This operating feature of NPPs can therefore be used profitably by the load dispatcher in providing for generation control during contingency operation when the NPP is operating at less than nominal power.

Conversely, during NPP down-times in a low-performance grid, generation control becomes a difficult task for the load dispatcher. An outage of the NPP will cause a substantial loss of generation of both MW and Mvar for the grid. The larger the size of the NPP, the higher will be the loss and the investments for larger spinning capacity and reactive power compensating equipment. The NPP size selection is of great technical and economic significance. The grid must have enough reserves to ensure system frequency stability during NPP down-times (refuelling and/or maintenance), and adequate loading strategies for the other units feeding into the system must be established to assist during scheduled outages.

4.3. Improving the nuclear power plant/grid interface

To achieve a smooth integration of the NPP into the system, the prospective owner of the NPP should verify that adequate operating capabilities, which are responsive to his functional requirements, are included in the NPP design; he should also consider improvements which would be economically feasible to be introduced in the grid to permit safe operation of the NPP.

4.3.1. Nuclear power plant design

The power set-back capabilities and the ability to resort to, and to extensively operate at, house-load conditions are important features of a NPP intended

[7] Running electric motors tend to maintain a constant megavolt ampere (MV·A). A voltage reduction will cause a current increase.

for a low-performance grid. These operating characteristics should be demonstrated, not only by design calculations but also by extensive operating experience with a NPP of the same type and size, built by the potential supplier of the envisaged NPP. During commissioning of the NPP, acceptance testing should demonstrate the 100% load rejection capability without turbine tripping on overspeed.

A point to be considered is that, upon a grid disturbance, if the NPP is immediately disconnected from the grid, its loss of generation is likely to add to the already disturbed conditions of the grid. To help maintain the stability of the system, the NPP should therefore be made as available as possible without compromising its safety. In this respect, all parameters which initiate a power set-back and/or a reactor trip should be critically studied and, as far as possible, their measurement should be made immune from grid-induced events by adequate delay equipment; thus it can be seen whether the NPP can sustain the disturbance, first by resorting to intermediate power levels and then to house-load operation, to prevent damage to equipment; a reactor trip should be the last means of ensuring safety.

Uninterrupted operation of the NPP is important for the system, more so at times of upset conditions when the grid needs the service of the NPP more and when its outage is likely to cause difficulty in maintaining the frequency.

4.3.1.1. When the voltage and frequency of the external grid vary, it should be possible to operate the turbogenerator set at the conditions indicated by its characteristics (see Figs 2, 4, 5). Margins for design modifications are very limited, since manufacturing of important equipment is to a large extent standardized. In a low-performance system, therefore, the grid characteristics and the performance of the protective devices have to be improved in order to meet the operational requirements of the turbogenerator set. Also, the design of high-capacity motors for operating conditions other than those normally prescribed by manufacturers is very special, expensive and inefficient, and it is not advisable to introduce such motors since their performance may not be guaranteed. Moreover, extending the start-up and running capabilities of such motors at excessively low voltage and frequency conditions may result in counter-effects:

- Increasing the torque of the motors to improve start-up performance in under-voltage conditions will have the effect of drawing an excessively high current and may create problems regarding transformers
- Enabling motors to deliver full pump flow at under-frequency conditions may prompt the operator to operate improperly at nominal power under degraded grid conditions.

4.3.1.2. If the NPP is not to participate in frequency control and/or load regulation, the speed and/or load governor of the turbine can be made insensitive to a certain frequency band and thus the turbine will no longer control the frequency. Also, within this frequency band, the generator output is fully dependent on reactor power/pressure and not on frequency. Above the prescribed frequency band, the speed governor assumes control and can send the steam partially or wholly to the condenser, directly by-passing the turbine. At the same time, reactor power may be reduced by the reactor regulating system to match the turbine load demand. Below the prescribed frequency band, the NPP may be islanded, together with a part of the system, and its generation brought down to safe power levels, or the NPP may even be separated from the system and operated at house load if the equipment can operate safely at these conditions for an extended period.

An alternative is to have a speed governor with variable droop setting and to set it at a droop level higher than that of other generating sets connected to the system. This is a compromise between no participation in frequency control, as in the first case, and full participation in frequency control, as in other units of the grid. Load limiters can be set accordingly at a predetermined value so that, on decreasing frequency, load assumptions are limited to the pre-set value. On increasing frequency, the speed governor will come into force and will reject load upon frequency rise and droop setting, and participate in load/frequency control.

It must be noticed that both alternatives, especially the first one, impose a heavier frequency control and load regulation duty on the other generating units. Their droop setting must be fixed at a value lower than that of the NPP and this may require careful appraisal of extensive backfitting.

4.3.2. Grid characteristics

For correct integration of a NPP into an existing power system, a number of actions should be taken in order to find out how the special requirements and operating characteristics of the selected NPP design can be accommodated best by the existing system for reliable and efficient operation.

Soon after NPP site selection, in a low-performance system the transmission lines should be strengthened, the desired power flow distribution secured, and the reliability of the grid power supply at the future connecting points of the NPP to the network improved in order to meet the reliability requirements of the NPP electric power system. In a low-performance system, the existing grid protection may not have the capability to satisfy the necessary effectiveness and reliability for safe NPP operation. Equipment may need to be modernized, protection strategies appraised, and relay discrimination and co-ordination improved. Foremost, the ability to clear a fault within 100–150 ms (5–8 cycles) is essential for safe NPP operation.

4.3.2.1. A co-ordination committee, comprised of personnel from the grid and from conventional and nuclear power stations, should meet periodically to discuss and solve various common problems, and to evolve and review operating procedures and strategies.

4.3.2.2. Generation scheduling studies should evaluate whether the NPP will operate on constant load or load-follow conditions, what will be the effects on the other thermal power stations and how best to optimize power generation.

4.3.2.3. Scheduling studies on maintenance and refuelling outages should reveal any problems in assuring system stability during NPP outages. An integrated maintenance schedule and loading strategy for the complete power plant system would emerge.

4.3.2.4. Studies on steady-state operation and transient stability should be performed under various simulated conditions of generation scheduling and transmission line configurations to reveal the weaknesses of the system under fault conditions. The results of these studies will enable proper remedial measures to be taken for system generation control in order to prevent the system from becoming unstable while enabling the NPP to withstand the disturbances and to continue operation.

4.3.2.5. System islanding after a disturbance should be done in such a way as to enable the NPP to maintain its generation to the extent possible. It is important to secure reliable means of dispatching the output power generated by the NPP to the load centres, in this way providing dependable load to the NPP at all times. After the disturbance, the load dispatcher should restore load gradually since otherwise some disturbance can occur again. For load restoration, the system load requirements as well as the characteristics of the NPP and of the other generating units operating in the system should be considered.

4.3.2.6. Flattening of the load curve: The load is not constant throughout the day and the ratio of maximum to minimum demand generally varies between 1.5 and 2. The aim of the power system managers is to bring the ratio as close to 1 as possible. Load management can be achieved by: (a) introduction of economic measures such as differential tariff to encourage off-peak loads (for pumping, storage heaters, etc.); (b) enforcement of administrative measures, such as restricting the use of non-essential loads during peak periods; (c) development of public co-operation, such as voluntary (or mandatory in extreme cases) staggering of working hours and holidays of factories and offices; and (d) development of a storage hydro-plant, if possible. If topography permits, a pumped storage scheme can be very effective in flattening the load curve; it supplies high-value power during peak hours and consumes low-value power at off-peak hours.

4.3.2.7. Optimization of reactive power flow and voltage profile: To maintain the voltage quality on the bus bar of the NPP, provisions for supplying reactive power should be made. Measures to be contemplated include: (a) Improvement of the power factor of the system and of individual loads, providing static compensators, shunt capacitor banks, synchronous condensers, series capacitors for long transmission lines, and on-load tap changers on certain power transformers. Some of these facilities may operate continuously or as required by the system conditions, and some may be automatically switched on or off during disturbances or in response to degraded conditions. (b) Location of the NPP near a power station with high availability; this may be helpful in voltage maintenance by supplying adequate reactive power.

The installation of the above-mentioned equipment should be carefully evaluated by assessing the benefits against the required investments.

4.3.2.8. Automatic load shedding: The introduction of such a scheme and its effective operation can significantly improve NPP performance during load generation imbalance caused by forced generation outage or line tripping. If the scheme is properly implemented, it might prevent system collapse; after a few seconds, the acceptable frequency and voltage may be re-established (see Appendix). If the NPP is properly designed, it will continue to generate electricity during the disturbance with no adverse effects on its lifetime. The continuity of power supply to most customers will also be maintained, thus facilitating timely resynchronizing of lost power generation. It should be mentioned, however, that the restoration of an active power balance by load shedding may create imbalance of reactive power; this would induce off-nominal voltage conditions which, if severe, are likely to create serious system disturbances unless appropriate reactive power control is provided.

Load shedding can be initiated by sensitive solid-state under-frequency relays installed at switching stations and load centres. Under certain severe grid disturbances the rate of frequency drop may be excessive and under-frequency relays with a time delay may be too slow to save the system from collapse. Under these conditions, rate-of-frequency-drop relays (df/dt), in conjunction with multiple under-frequency relays with different under-frequency settings and time delays, may be helpful.

4.3.2.9. System islanding and sequential load restoration: Under disturbed grid conditions, keeping a station or unit connected to the grid may result in outage or damage of costly and vital NPP equipment. Thus, a scheme for isolating the station or unit from the grid is often followed as an ultimate strategy.

After separation, the station auxiliaries continue to be supplied by the unit at good voltage and frequency, and the NPP output is reduced by the automatic power set-back system to predetermined values compatible with the local loads and the capacity of other generating units in the isolated system. The unit/station thus 'islanded' from the grid can be re-connected when the fault is isolated and normal conditions are restored in the grid, and the unit/station can then be progressively re-loaded to nominal power.

The limits of frequency and voltage at which the unit may be islanded should be very carefully chosen. If they are too conservative, there would be frequent disturbances in the grid because of loss of generation; if they are too liberal, the NPP may trip before islanding or important equipment may be damaged.

In the case of severe transients, when the grid frequency is dropping fast, the under-frequency relays with fixed setting may prove inadequate. In this case, the equipment suggested for effective load shedding under severe transient conditions can be used (see 4.3.2.8).

4.3.2.10. Peak power supply: Special measures must be taken by the utility to cope with load requirements at peak load conditions. Peak power supply can be made available by means such as the following: (a) borrowing power during peak hours from neighbour utilities if provisions for adequate interconnection between grids exist; and (b) installing adequate quick-start capacity. This capacity is provided by units which can be started in a few minutes to take care of the peak demand. Hydro power stations with or without pumped storage and gas turbine or diesel-driven generators can be used for tiding over peak power supply problems. An interesting possibility for a more effective use of this expensive quick-start capacity is to locate an adequate part of it at the NPP premises and to use it for emergency start-up. However, if the on-site power supplies are used for peaking service, extra capacity may be required to ensure availability in case of need to provide shut-down power.

4.3.2.11. Load dispatching: Secondary control in its wider perspective does not come under the purview of this Guidebook. However, those aspects of it which will help in maintaining good quality of voltage and frequency throughout the grid and especially at the NPP are briefly mentioned as being relevant to NPP operation.

The efficient integration of any plant into the economic load-sharing programme of a network requires a means of adjusting the plant output to the load requirements of the system. NPPs are no exception. At any given time, the power output of the NPP is determined by the load dispatcher. Economic dispatching requires minute-by-minute grid demand analysis and minute-by-minute power plant output adjustments. In order to respond to the requirements of an integrated economic control scheme of an electric system, some units in the generating system must feature load-follow capability. If the NPP is among these, the load dispatcher must be informed of how much of the NPP capacity is currently available for his utilization. Most restrictive are step-change capabilities, which represent the minimum power-change capacity that can be supplied by the plant, whereas power ramp rates generally allow large power changes. There are two factors involved in the plant step-change capabilities: those of the NSSS and those of the BOP. The NSSS capabilities are determined directly in the reactor power control system and are a function of the core burn-up (see Section 3.5). The determination of the power-change capabilities of the BOP is different from that applied for the NSSS. Generally, the BOP can accommodate any power change possible in the NSSS except plant start-up from cold when appropriate BOP restrictions are assigned. The net output to the remote dispatching terminal will be the minimum of the NSSS and BOP capabilities. An updated plant step-change capability must be continuously available to the dispatcher. The dispatcher is free to change NPP power output within this limit if a plant operator permission is given. The permission can be manually withdrawn at any time, or it will be withdrawn automatically whenever plant trip conditions are approached (run-back, stop, hold signals). In either case, plant control will return to the operator.

5. ANALYSIS OF THE POWER SYSTEM CHARACTERISTICS

5.1. Data base of the existing system

During NPP feasibility evaluation, the prospective owner must begin discussions with consultants, architect/engineers, vendors and licensing authorities. Therefore, comprehensive information on the characteristics of the present electric system and their projection to the time of NPP commissioning must be available. The essential data of standardized design of commercial NPPs are generally available from manufacturers. However, this is not necessarily so with some information on the dynamic behaviour of the system and the existing power stations in normal operation and under fault conditions. Calculations necessary to investigate the dynamic system behaviour require a large amount of data which cannot be made readily available when needed unless appropriate and timely monitoring of the system is initiated. Grid studies and monitoring should be initiated early enough to facilitate a good statistical understanding of the system performance and its dynamic behaviour during transient as well as steady-state conditions.

The prospective owner of the NPP is therefore advised to create at an early stage a comprehensive data bank and to perform in-depth analysis for integrating the NPP into his electric grid. By doing so and by sharing this information as early as possible with the planners, designers and suppliers, he will succeed in obtaining a NPP which is more responsive to his requirements. Considering the economic penalties associated with NPP outages and the cost of late backfitting, the necessity of proper understanding of the problems involved and of seeking possible remedies to mitigate them must be stressed.

As a first step, only the existing system and its power stations before NPP integration are taken into consideration, with the following aims:

- to obtain details of the dynamic behaviour of the power system
- to recognize possible malfunctions and/or inadequacy of the grid protection system and to identify possible improvements
- to test and, where necessary, improve system simulation by comparison with system dynamic behaviour recorded in similar occurrences which have been monitored.

This serves as a basis for the studies which have to be carried out in conjunction with the planning of the NPP.

In the following, the relevant data to be measured, modalities of measuring, adequacy of instrumentation and format of recording are reported. The data bank should be capable of storing a large amount of readings. Data must be adequately classified and stored so that they are readily retrievable for use.

5.1.1. Non-monitored data

These data are extensively used also for planning of conventional expansion of the system and are, therefore, not elaborated upon in detail. The data should include one line diagram of the system, impedance diagrams, data on power plants, transmission lines, transformers, loads on the system, control schemes, protection and automation. Most of these data are available in the utility and are used for load-flow and short-circuit calculations and for stability studies.

The data should include the utility operating criteria, i.e. directives on permissible frequency and voltage variations; requirements for cold, hot and spinning reserve; operation of hydro, pumped-storage, diesel and gas-turbine generators, and load shedding and islanding procedures.

The data should be brought up to date on, at least, a yearly basis.

The data should refer in detail to the grid which has to integrate the NPP and also to neighbouring grids which are expected to be interconnected during the first years of NPP operation. If appropriate and accurate data concerning neighbouring grids are not available, it should at least be possible to use a simplified model of the neighbour system whose parameters should be verified by special monitoring.

5.1.2. Data from continuous monitoring

The following data should be obtained by continuous monitoring at the most critical points of the grid and particularly at the prospective connecting points of the NPP:

- Hourly grid load values for at least one year, preferably in a form suitable for computer processing

– Comprehensive data on load flow during normal and extreme system conditions, i.e. maximum and minimum demand, summer/winter and day/night demand, and load flow for scheduled outages of power generation and transmission
– Statistics of forced outages of power plants and transmission lines, using an appropriate code for reporting
– Voltage and frequency profile at the points of future NPP connection to the grid, monitored by voltage and frequency recorders.

Such recording can be performed by simple electromechanical chart recorders or by more sophisticated digital devices. Digital devices enable better data processing and quicker access and retrieval of information. The advantage of using charts and other analogue recordings is that they can be evaluated by hand or with the help of a digitizer, provided that reliable information on the time scale and recording speed and values is clearly given on the charts.

The analysis of these data should consider normal operating conditions and disturbances.

5.1.2.1. Normal operating conditions

Under normal operating conditions, frequency and voltage fluctuations at critical points of the grid should be monitored:
– over long periods on a monthly/yearly basis
– over medium periods on an hourly/daily basis
– particularly during load fluctuations and switching operations, in the range of minutes.

When monitoring the frequency response, the following additional information should also be recorded:
– power stations being operated in the frequency control mode
– setting of speed droop characteristics in the system units.

5.1.2.2. Disturbances not involving loss of generating capacity

These disturbances typically include short circuits and load swings. Records to be maintained during such events should include:
– number, types, locations and frequency of faults, duration of the fault clearing time, performance of protective devices
– availability and effectiveness of the protective systems
– number, cause, amplitude, frequency, damping of load swings and corrective actions taken.

Sometimes, faults occur for no obvious reasons. Typically, they include swings between system sections (system inter-tie oscillations).

Complete information should be obtained on how often such faults lead to other faults in the system and on the related causes. Also fault statistics should be included. This information is the basis of a fault-tree/event-tree analysis.

The data listed under 5.1.2.1 and 5.1.2.2 give indications regarding the correct relay setting for frequency-controlled load shedding and the control and protection system.

5.1.2.3. Disturbances involving loss of generating capacity

When large power station units or essential tie lines fail, the system behaviour must be recorded. Particularly relevant are data on the variation of power, frequency and voltage, as well as information on the performance of the load-shedding system and of the protection and control equipment.

The data gathered during the disturbances should be checked for consistency with other relevant system parameters measured and recorded during other system disturbances. This analysis will provide a good understanding of the system inertia (normally, about 1.5–2 times the inertia of operating turbo-sets) and of the system capacity.

It is essential to make a list of the reserve capacities available in the system at any time in order to know what reserves can be mobilized in the event of a fault. Some reserves can be activated rapidly but are limited in time and involve economic penalties; these reserves will be replaced in time by reserves that are slower but available for longer periods so that the power required is available until complete system recovery. Economic aspects play a major role in this analysis.

The size and type of system reserves can be classified with respect to the time necessary to make them available.

Reserve capacity	*Coming into effect*
Moments of inertia	immediately
Diesel generator sets	in 10–20 seconds
Spinning reserves	in a matter of seconds to minutes
Switching in gas turbines	in 3–5 minutes
'Warm' stand-by	in minutes to hours
'Cold' stand-by	in hours to days

5.1.3. Data from special monitoring

Apart from continuous monitoring by slow-speed apparatus, the prospective plant owner should consider special ad hoc monitoring. Information obtained in this way may provide a better understanding of the local operating conditions and is therefore recommended; such monitoring can, however, not always be shown to be indispensable for NPP integration into the grid.

5.1.3.1. High-speed frequency recording during normal operating conditions

During normal operating conditions, a sampling frequency at intervals of one to ten seconds during a period of 15 minutes to 1 hour should be considered. High-speed chart recorders or counters with limited digital memory can be used for this purpose. Ten to twenty such recordings during different load and generation configurations should be performed. Frequency fluctuations which may influence NPP control design, as well as areas of possible vibration, fatigue, etc. can be detected by high-speed recording.

5.1.3.2. High-speed frequency recording during disturbances

Frequency recording during unit outages, tie-line switching, load shedding and unit islanding will provide meaningful information. Instrumentation similar to that mentioned in 5.1.3.1 can be used to obtain data at 0.1 second intervals, the system being triggered on detection of abnormal conditions. The results could be used to advantage for NPP/grid interaction by allowing calibration of models for dynamic simulation; ultimately, undesired trips of the NPP could be precluded or minimized.

5.1.3.3. High-speed voltage recording during disturbances

Such recording should be performed automatically at the point of future NPP connection to the grid during short circuits, forced outages of generation and transmission lines, load shedding and unit islanding. The voltage can be recorded by a fault detector, an oscillo-perturbograph or a digital device with memory. The information from such recording can help to improve the setting of the protective relays and the control scheme of the NPP, taking into account the effects of adding the NPP at that point in the grid.

5.2. *Improvement of system monitoring*

The analyses of system disturbances and faults produce valuable information to be used for improvement of the dynamic system behaviour and for determining and testing suitable mathematical models. However, appropriate measuring facilities and means for proper evaluation of the readings obtained are required for these analyses.

In the event of fault conditions taking place in the range of seconds, there must be a sufficiently accurate chronological sequence of the phenomena taking place at various points in the system. Time recording by manual means often proves to be unsuitable. Particular attention should be paid to the adopted time resolution and scaling, since not only high-speed phenomena in the range of seconds but also slow phenomena in the range of minutes are involved.

To assess the adequacy of the data monitoring and recording system, the following steps should be taken:

- Checking of the existing measuring facilities: All of them must function correctly; the results must be recorded and evaluated in a suitable form.
- Compilation of the data required for analysing the system behaviour: The relevant additional measuring facilities which would be desirable and their costs should be listed.
- Selection of suitable measuring facilities, with due regard to their effectiveness and cost: This should also take account of possible future extensions. It is imperative that the measuring facilities be suitable for the specified purpose.

5.2.1. Additional data on the existing supply system

Sometimes the data available are not sufficient to provide the necessary inputs for modelling NPP/grid interaction. The data most frequently missing include: system load as affected by frequency and voltage, generating plant response to disturbances, governor and excitation system characteristics, time constants.

Such modelling inputs can be estimated on the basis of theoretical considerations and of experience obtained from other systems or from special tests and measurements. This is particularly the case when the system includes old units for which relevant data from the manufacturer are no longer readily obtainable.

5.2.2. Data processing and storage

The format of the data, the extent of data processing and the type of data storage should be decided by the plant owner on the basis of the available facilities and cost considerations. Digital representation suitable for computerized data processing should be considered whenever economically justified. Complete preservation of the data, with detailed reference to time, system configuration, type of monitoring device, sensitivity, accuracy, speed of recording, etc., is strongly recommended. Therefore, an extensive storage effort should be planned.

5.3. Evolution of grid characteristics

The electric grid is dynamically evolving and, during the 8–12 years between the decision to install the NPP and its commissioning, important changes may take place. The load demand may grow, the load-curve shape may change, new transmission configurations may evolve, old units and equipment may be scrapped or modified, and improvements may be introduced.

Some changes in the grid are independent of the decision to introduce a NPP, but they may influence its future integration into the grid. These changes should be assessed by the owner as follows:

- Provision of regional load forecasts and of in-service schedules for the new generating units
- Assessment of the performance of the future protection and control system
- Assessment of the development of the transmission network, considering the implementation of better load management and load dispatching
- Assessment of future social and industrial requirements of the country, since their influence may change the power demand pattern and therefore the shape of the load curve. Man-induced events, such as spraying of crops, vandalism and air pollution, may influence the forced outage rate. The demand for quality and continuity of electricity supply may undergo changes.[8]

These changes should be assessed and their impact upon grid development should be estimated for the period up to the planned NPP integration into the grid. Some of these changes will introduce positive effects:

- Replacement of old equipment by modern, more advanced equipment will reduce the frequency of faults
- Additional circuits, a higher degree of meshing and static capacitors may be introduced
- Load dispatching centres, better communication and automation may become operational
- Interconnection with neighbouring systems (higher reserves in case of unexpected unit outage) could become possible
- Grid protection and power station control systems may be improved.

Other changes may have negative effects:

- The generation control capability of the system may become smaller (when old power stations with good control characteristics are taken out of service)
- Higher load demands for quality and availability of electric power may limit load-shedding schemes
- Major problems regarding load swings may result from interconnection with neighbouring systems
- The capacity of the transmission system may not increase at the same pace as the capacity of the generating system.

[8] These are items which play the most important role in the decision to add generating capacity. They must be evaluated at the outset of any studies. Changes during the design and construction phases can have a serious effect on the project.

5.3.1. Updating of grid information

The evolving grid characteristics and future changes in the input data should be critically reviewed in order to estimate the grid behaviour at the time of NPP commissioning and thereafter. Different development scenarios should be investigated to check the sensitivity of the results of the anticipated changes.

5.4. Modelling of nuclear power plant integration into the grid

When contemplating system expansion and integration of new generating units (conventional or nuclear), load-flow and short-circuit calculations as well as transient stability analysis should be carried out for different operating conditions. Computer codes for these calculations are available and widely used by grid planners and operators, consultants and architect/engineers, equipment manufacturers and research institutions. The results of these studies can be used to predict system requirements, to calculate voltage profile and fluctuations, to detect undesirable conditions and to suggest remedial measures.

However, reliable input data are not always available, especially data referring to load dependence upon frequency and voltage. Sometimes the equipment capabilities and characteristics are not known in sufficient detail, particularly with respect to the old units still in operation. NPP behaviour, however, has been modelled extensively by manufacturers and operators.

The prospective NPP owner is encouraged to familiarize himself with the existing computer programs. He may consider to perform these calculations for his grid and to compare the results with fast frequency and voltage recordings during disturbances. By doing this, he can check the data and calibrate the models, in order to be prepared for the simulation of NPP performance in the grid.

The calculations to be performed depend upon the specific problems being investigated. Therefore, various models valid for different time ranges should be considered. When simulating the behaviour of the system during disturbances not involving loss of generation, the calculations should extend beyond the first few seconds after fault inception since, in some cases, dynamic stability may be lost within 3–30 seconds. Therefore, models for two time ranges should be used:

- Models capable to simulate the system in a time range of up to 1 second. The turbine and voltage controller do not need to be simulated or only in a very simplified form; this analysis requires a modest amount of data. The results indicate whether system stability can be maintained under short-circuit conditions.
- Models capable to simulate the system in a time range of up to 30 seconds. Mathematical replication of the turbine, including its control gear, as well as

of the generator voltage controller and protective devices is required. The results indicate whether load swings, which occur after disturbances or in normal operation, are increasingly damped, or undamped, or even uncontrolled, and what remedial action can be taken.

When simulating the behaviour of the system during disturbances involving loss of generation, mid-term and long-term simulations of electric power systems should be done. The mid-term simulation deals with transients of up to 5 minutes and includes the response of the prime mover and transmission system to changes in generation, and transient stability calculations providing information on inter-unit oscillations. The long-term simulation may be done by using a suitable model permitting the use of one second step and should be capable of simulating disturbances lasting up to 20 minutes. The input data in these calculations include the parameters for the steam generator, the turbine, the electric generator, and the equipment of the frequency-controlled load-shedding scheme and the secondary control system.

The results of these calculations can display the evolution of a fault condition until system recovery and thus enable an overview and a complete assessment of the entire system dynamics. Information on active and reactive power flow, steam flow, frequency and voltage, angles and other time-dependent variables is obtained.

The number of data required is much higher than for disturbances not involving loss of generation and the data acquisition may prove a difficult task.

When modelling the system, the following points should be considered:

- The complexity of a mathematical model must be balanced against the required accuracy of the simulation.
- The model is valid only for the occurrence it simulates and for well-defined time ranges.
- A great number of data can be obtained from the manufacturer of the equipment to be simulated.
- If simulation of old units is needed, the relevant data may have to be derived from special measurements and/or operating tests; data gathering may become difficult.
- In case of interconnection with neighbouring systems the relevant data should be known preferably with the same accuracy.
- The model should be structured so that it can be expanded in steps, i.e. on a modular pattern, from a simple simulation up to a very complex one, in order to suit different analysis requirements. Care must be taken to check for consistency at the interface of various modules and to remove ambiguities. It should be considered that sophisticated models are only meaningful if the relevant data can be obtained with adequate accuracy. If this is not possible, a simplified model may prove more useful.

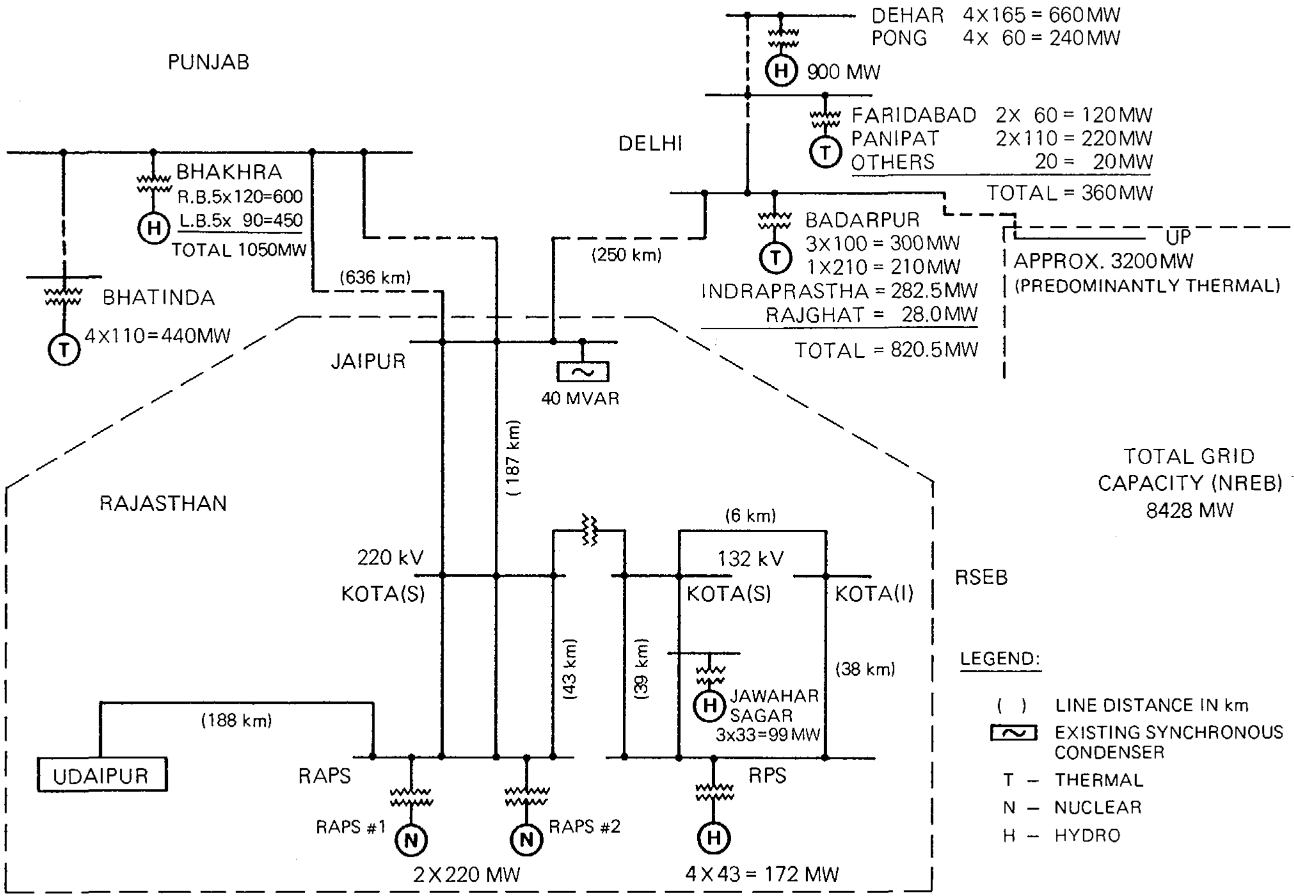

FIG.A-1. Main transmission lines connecting RAPS with the NREB grid.

– When a mathematical model for the system becomes available, it must be tested by calculating specially selected real fault conditions. In this way, it can be seen to what degree the mathematical model is able to replicate actual conditions. In the case of major deviations, better agreement may be achieved by changing certain specific parameters. This is also important for simulating the effect of neighbouring systems (interconnected systems operation with other countries, for example) if no details are available and simplified, empirical models have to be used.

Appendix

CASE STUDIES

A series of case studies derived from real occurrences are reported. The first five cases are part of the operating experience accumulated at the Rajasthan Atomic Power Station. The last case presents the operating strategy adopted by a utility (the Israel Electric Corporation) to control power generation in a limited system incorporating a relatively large unit and with reduced provision for spinning reserve.

This Appendix may represent a useful guidance for the users of the Guidebook in specific case problems.

A-1. LOW-PERFORMANCE GRID INCORPORATING A NUCLEAR POWER PLANT

The Rajasthan Atomic Power Station (RAPS) consists of two units of 220 MW(e) with pressurized heavy water reactors. It is situated in the state of Rajasthan and is connected to the grid of the Rajasthan State Electricity Board (RSEB) by 220 kV transmission lines. RSEB itself forms part of the Northern Region Electricity Board (NREB) to which grids of other states of northern India are also connected (India is divided into five regional grids: west, east, north, south and north-east).

The installed capacities of NREB are as follows:

Thermal	3938 MW(e)	(210 MW(e), largest unit in Badarpur)
Hydro	4050 MW(e)	(165 MW(e), largest unit in Dehar)
Nuclear	440 MW(e)	(2 units of 220 MW(e), RAPS)
Total	8428 MW(e)	

Figure A-1 shows the main transmission lines connecting RAPS with NREB.

The salient points to be noted are as follows:

– RAPS is almost in the far end of the grid and separated by more than 400 km of transmission lines from other large generating centres. Two hydro stations of comparatively smaller capacities are situated near RAPS but are not able to participate very effectively because their capacities are small; also, their availability is often governed by other considerations, such as irrigation demand and poor hydrological conditions.
– Synchronous condensers are available at Jaipur, but there is no voltage control equipment at Kota, RAPS and Udaipur.

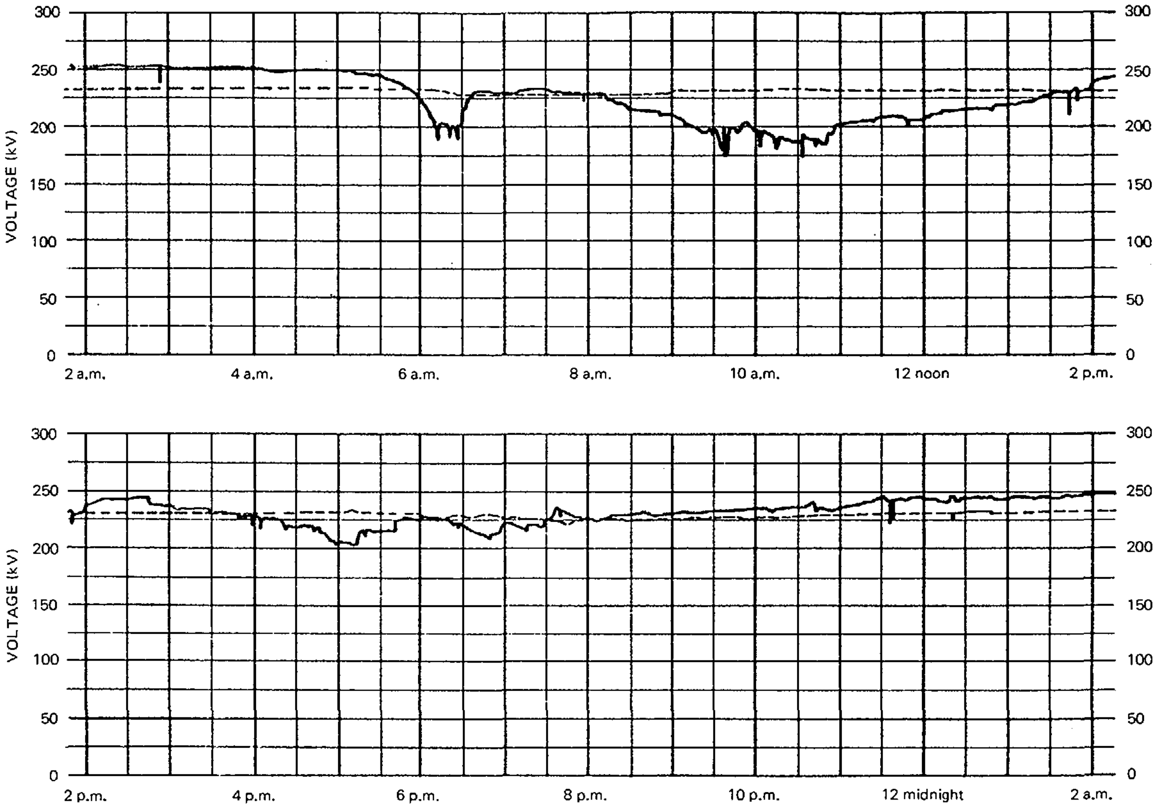

FIG.A-2. Grid voltage.
– – – RAPS operating on 30 April 1981
——— RAPS not operating on 17 April 1981.

– When RAPS is operating, the voltage around RAPS can be reasonably maintained. However, when RAPS is not operating, power has to be transmitted from far-away places like the Badarpur Thermal Power Station or the Bhakra Nangal Hydro Complex. So, although the voltage may be reasonably maintained in the Badarpur and Bhakra areas, the voltage at RAPS and Udaipur is governed mostly by a drop due to power flow and capacitive load of the high-voltage transmission lines.

During peak periods when the loads are high, the transmission line drops are too sharp, causing low-voltage conditions at RAPS. On the other hand, during off-peak periods in the night when the grid in the Rajasthan area is very lightly loaded, the voltage at RAPS rises because of a capacitance effect of the long transmission lines (Ferro-resonance or Ferranti effect). The situation becomes worse because of the fact that, when RAPS is not operating, the Rajasthan grid is not able to meet the full power demand of the consumers and the grid operators are forced to resort to load shedding, as a result of which the grid becomes more lightly loaded. A 400 MW(e) power station is being built in the vicinity of RAPS near Kota; when this station goes into operation, the voltage problem may be alleviated.

Case 1

Prolonged off-normal voltage operation

Figure A-2 shows the voltages at the RAPS 220 kV bus. One curve indicates the voltage when the units are operating, the other curve indicates the voltage when the units are not operating. It can be seen that when RAPS is operating, the voltages are more or less normal within a band of 5 kV, varying between 230 and 225 kV. The voltage drops slightly to 220 kV during peak hours of the morning and evening. When RAPS is not operating, the voltage drops to 185 kV (momentarily touching 175 kV) and to 200 kV during peak hours of the morning and evening, respectively. It can also be observed that the voltage remains generally low between 8 a.m. and 7 p.m., which makes it difficult for large coolant pump motors to be started or run. If they are started, they trip on stall protection; if they are operating as a prelude to start-up of the unit, they trip on overload. The overload effect is felt more severely during reactor start-up from cold conditions because the pumps have to pump up cold fluid and hence need a higher current than when the reactor is started from hot conditions. So reactor start-up is often restricted to night hours when the voltage is high. Here again, if the voltage is too high, sometimes the pump motors trip on instantaneous actuation of the over-current relay.

It can be seen from the figure that when RAPS is not operating, the voltage can be as high as 250 kV during the night. Even when RAPS is operating, the voltage rises because of a very high capacitive loading of the transmission lines during the night and RAPS is forced to take high values of leading Mvar, which causes an unstable situation for the RAPS machines.

Remarks

(a) The high and low voltage conditions at the RAPS 220 kV bus when RAPS is not operating are due to: (i) the absence of voltage control equipment, (ii) the absence of comparatively large thermal or hydro stations near RAPS, and (iii) the fact that the existing large stations are situated far away. The situation could be improved by providing voltage control equipment, such as reactors, capacitors or synchronous condensers in the 220 kV bus.

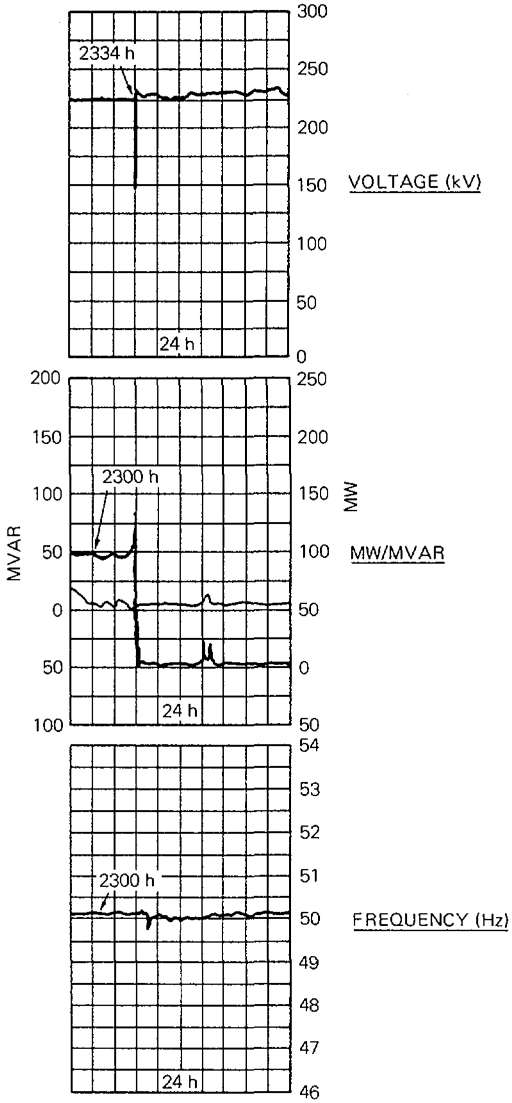

FIG.A-3. Case 2: Unit outage due to voltage dip on 30 May 1980.

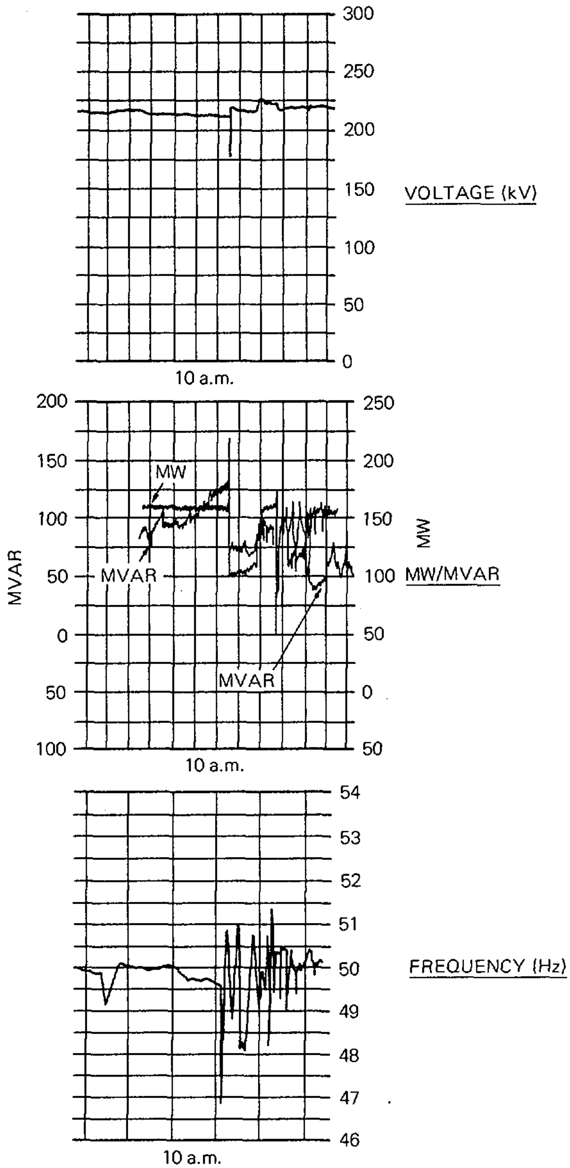

FIG.A-4. Case 3: Example of successful islanding.

(b) Problems due to low voltage exist for the low-voltage auxiliaries because of the absence of an on-load tap-changing facility in the unit auxiliary transformers of RAPS.

(c) The desirability of an on-load tap-changing facility on the station auxiliary supply transformer ought to be studied on a cost/benefit basis.

Case 2

Unit outage due to voltage dip

On 30 May 1980, RAPS unit 1 was operating at 95 MW(e). At 23.34 hours, a sharp voltage dip from 225 kV to 145 kV was recorded, as can be seen in Fig.A-3. There was a fault on a 132 kV system near the Kota industrial area (KOTA-I of Fig.A-1) which was being fed by two lines, RAPS-KOTA(I) and KOTA(S)-KOTA(I). The RAPS-KOTA(I) line tripped on distance protection, but KOTA(S)-KOTA(I) tripped only on back-up protection. A slight delay in clearance of the fault caused a sustained voltage dip, and four main circulating pumps in RAPS tripped on under-power relay protection, resulting in a reactor trip.

Remarks

(a) The reason for the unit outage was the persistence of low voltage for a comparatively long time, sufficient to initiate the under-power relay. The fault could not be cleared fast enough because of the absence of distance protection relays. Fast relays should be installed for quick fault identification.

(b) An islanding scheme for NPPs to be used on voltage dips for longer periods may be introduced. The actual duration of the dip may be arrived at after taking into account the detection time of the relays and the clearing time of the breakers.

Case 3

Successful islanding

On 19 September 1980, RAPS unit 1 was operating at 160 MW(e). At 10.10 hours, the interconnection lines between Bhakra and the rest of the grid tripped, cutting off 850 MW(e) from the system. This resulted in a frequency drop to 46.8 Hz in the rest of the grid (see Fig.A-4), tripping most of the running units in this region.

The Jaipur-Kota lines tripped on under-frequency protection, set at 47.5 Hz. RAPS was isolated by manually tripping the RAPS-KOTA lines. RAPS was then operated by feeding load from Udaipur radially at around 125 MW(e) until 10.32 hours when RAPS was synchronized with KOTA (RSEB grid). The frequency control was not good, as can be seen from the figure, until RSEB was synchronized with NREB at 11.07 hours. Thereafter, the frequency improved.

Remarks

The under-frequency isolation scheme worked satisfactorily. The scheme is as follows:

47.5 Hz	inst.:	KOTA-JAIPUR lines trip
47.5 Hz	2 min:	RAPS-KOTA lines trip
46.5 Hz	inst.:	RAPS-KOTA lines trip.

After islanding, the frequency control in the islanded Rajasthan grid was not proper, which resulted in frequency oscillations; these were attenuated when the Rajasthan grid was re-connected with NREB.

Case 4

Set-back rate reduction

It is worth noting that, if the power set-back rate is too high, it may result in reducing power too fast and to a lower value than is required. In this case, there may be a quenching effect, culminating in a low-pressure trip of the heat transfer system (HTS). In RAPS, the set-back rate was previously 1% of full power per second, which used to result in too fast a rate of power reduction and consequent low-pressure trip of the HTS. The set-back rate was later decreased to 0.5% of full power per second and the system stability improved.

On 5 June 1977, RAPS unit 1 was operating at 160 MW(e) when there was a reactor set-back due to problems at the station. Power generation came down to zero. The reactive power went up from 23 to 52 Mvar. The HTS pressure dropped from 86.5 to 82 kg/cm^2. There was no appreciable effect on grid voltage. The frequency dropped from 49.4 to 47.6 Hz. The power generation was raised again to 160 MW(e) in approximately 15 minutes.

The unit survived on controlled reduction of power under set-back conditions and did not trip on low HTS pressure.

Remarks

(a) Reduction of the set-back rate from 1.0% of full power per second to 0.5% of full power per second helped the station to keep up operation.

(b) Reduction of the low-pressure trip setting of the HTS from 84 to 74 kg/cm^2 also helped to avoid a low-pressure trip of the reactor.

Case 5

Voltage and frequency disturbances

Typical cases of grid disturbances in voltage and frequency are given below.

5.1. On 25 April 1976, at 12.50 hours, RAPS generation came down to house-load from 100 MW(e) when the RAPS-KOTA feeders tripped on earth fault:

Frequency:	50 – 52.7 – 52.6 (10 min.), down to 50.6 – 50 Hz
Voltage dip:	235 – 170 – 250 – 235 kV
Generation:	100 – 12, gradually to 100 MW.

The unit survived.

5.2. On 27 April 1976, the following grid fluctuations were observed:

Frequency:	49.8 – 48.8 – 46.1 – 51.9 – 50.5 Hz
Voltage:	230 – 194 – 277 – 240 kV
Generation:	160 – 175 – 25 MW.

The unit survived.

5.3. On 4 February 1976, the reactor tripped on high HTS pressure due to grid fluctuation:

Frequency:	49.4 – 50 Hz
Voltage:	235 – 300 kV
Generation:	175 – 185 – 0 MW.

The unit did not survive.

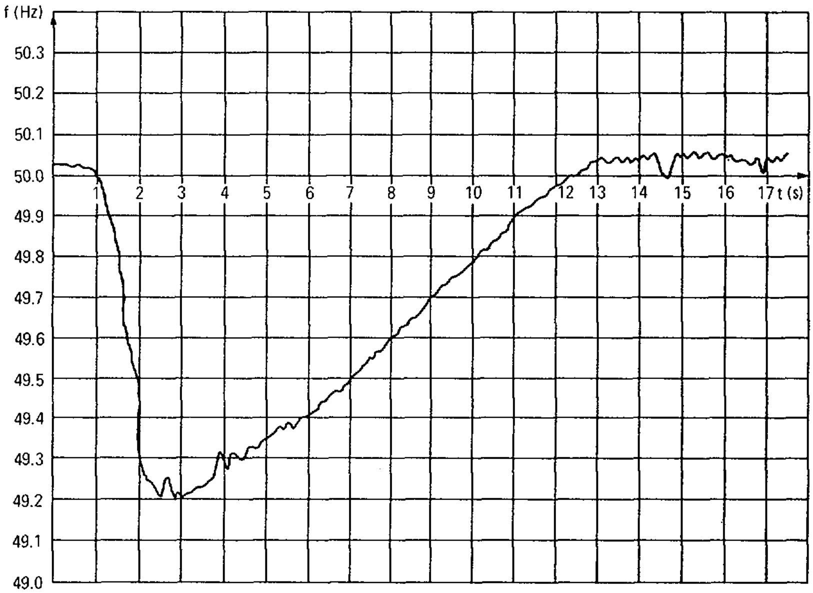

FIG.A-5. Forced outage of 210 MW; short-term frequency response.

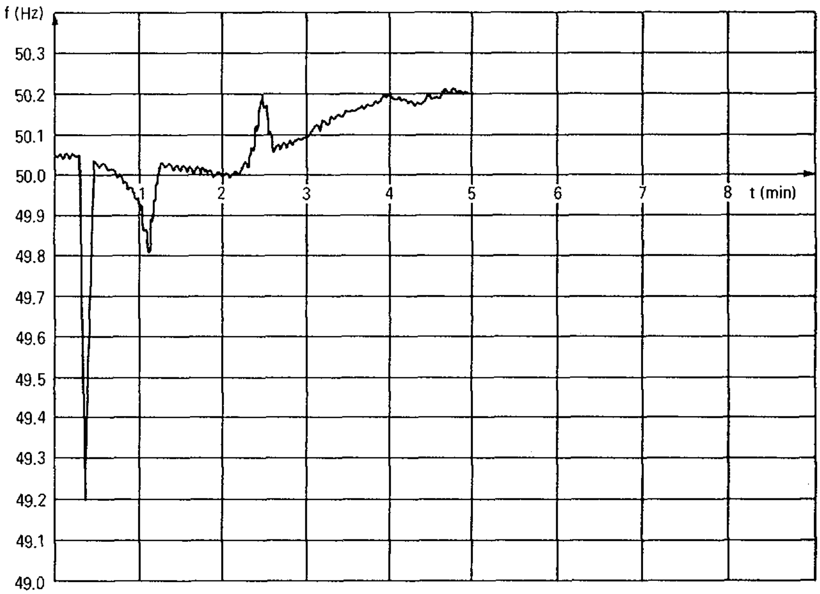

FIG.A-6. Forced outage of 210 MW; long-term frequency response.

5.4. On 8 September 1976, the grid voltage was 240 kV, then it went up to 255 kV and came down to 250 kV, remaining at this value for 30 minutes.

The unit survived.

5.5. On 24 August 1976, after severe grid fluctuations, the reactor tripped 'on less than two pumps' (presumably the pumps tripped on under-power due to extremely low voltage).

Frequency:	50 – 49.0, slowly to 49.2, slowly to 50.2 Hz
Voltage:	240 – 55 – 275 kV
Generation:	175 – 0 MW.

The unit tripped.

5.6. On 31 October 1979, the grid frequency came down from 49.6 to 47.7 Hz.

The unit survived.

Remarks

It can be seen from the above case studies that RAPS has survived frequency dips down to 46.1 Hz and frequency rises up to 52.7 Hz, and voltage dips down to 170 kV.

A-2. SMALL GRID INCORPORATING A GENERATING UNIT WITH RELATIVELY HIGH NOMINAL RATING

Case history – Israel national grid:

Maximum grid demand	2200 MW
Largest unit	350 MW nominal rating
System yearly load factor	66%, flat load curve
Generation	fossil only

Operation geared toward maximum fuel economy

Prolonged operation with no spinning reserve

During low demand periods, the output of a single unit may cover more than 30% of the total generation.

Acceptable availability of energy supply is maintained by:

- high performance of generating units – low forced outage rate
- comprehensive load shedding by static under-frequency relays
- remote start-up and quick loading of jet-type gas turbines
- automatic restoration of the load shed by static over-frequency relays.

The system is designed so that a trip of the largest unit or even simultaneous tripping of two largest units will be controlled by selective load shedding.

Most of the distribution lines in substations are provided with three levels of under-frequency load shedding:

49.4 Hz	0.2–0.5 s
49.0 Hz	0.4–0.7 s
48.6 Hz	0.6–1.0 s

The load shedding covers over 50% of the system load.

Transmission lines providing supply for emergency services and selective industrial plants are exempt from load shedding. The load shedding and sequential load restoration scheme includes the following steps:

– Since the system is operated with minimum provision for spinning reserve, on a unit outage the frequency falls and under-frequency relays located in the substations shed load selectively at a total of 80–120% of the capacity of the lost unit
– In 3–10 seconds, the frequency recovers to near normal after an initial frequency drop depending upon system inertia
– In approximately 5 minutes, remotely operated jet-type gas turbines are started and loaded, and the frequency is maintained slightly higher, at about 50.1 Hz, to enable re-connection of load without deterioration of frequency
– Loads which had been shed earlier are restored sequentially in steps by over-frequency relays
– In 10–15 minutes, the system normally recovers and the gas turbines which are no longer needed are shut down.

The system frequency is monitored at intervals of 0.1 s by a digital device with memory and a 'post-trip' retrieval facility. The print-out typically includes the frequencies during two minutes before the occurrence and during eight minutes after the occurrence.

Case 6

Tripping of 18% of generation

System load before unit trip	1142 MW
System frequency before unit trip	50 Hz ± 0.06 Hz
Unit tripped (225 MW capacity), operating at	210 MW
Spinning reserve	170 MW
Load shed	180 MW
Frequency drop to	49.2 Hz
Frequency restoration after load shedding in	11 s

The frequency behaviour is shown in Figs A-5 and A-6.
The load was completely restored after 10 minutes.

LIST OF PARTICIPANTS

The following meetings were held in Vienna with the purpose of assisting the IAEA in the preparation of this Guidebook:

Advisory Group Meeting	6–10 October 1980
Consultants' Meeting	2–5 March 1981
Consultants' Meeting	9–20 November 1981

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