Grid Stability and Safety Issues Associated with Nuclear Power Plants

Dr. John H. Bickel
Evergreen Safety and Reliability Technologies, LLC

1.0 Introduction

Nuclear Power Plants (NPPs) are used in many countries as an economical and environmentally clean source of base load electrical generation. However, the deployment of NPPs to supply a portion of the electricity on a power grid brings with it a number of requirements on the grid design that are unique to this power source, and which must be considered by power grid planners and system operators. Unlike conventional power sources (thermal power units, or hydroelectric dams), NPPs have long term shutdown cooling requirements that consume power and have stringent voltage and frequency limitations (imposed to assure the operability of critical emergency cooling systems). This paper attempts to briefly summarize the important technical issues involving grid reliability and nuclear safety, and how these are addressed by design standards and safety regulations.

2.0 Nuclear Safety Considerations

A key difference between nuclear and conventional power plants is the heat that must be removed following a full plant trip. All thermal power plants that are run at elevated temperatures require time to shut off the heat source, (be it from oil or coal combustion) and to cool down metal components without damaging boiler tubes or furnace walls. A nuclear reactor, even with the chain reaction completely shut down, will generate significant heat from fission product decay that persists on a logarithmic time scale as shown on the next page in Figure 1.

Figure 1, on the following page, is based on the ANS standard decay heat model as applied to a 1300 MW_e NPP. The implication of the decay heat curve is that a reliable means of long-term decay heat removal is required in order to prevent long term overheating of the reactor fuel elements. Typically the decay heat removal process is dependent on availability of a long-term stable source of electric power – either from the grid or from on-site power sources.

3.0 Nature of Grid Disturbances

Grid disturbances and occasional “Blackouts” periodically occur even in highly inter-connected electrical grids such as in the US. While the ability to provide redundancy in transmission pathways and generating sources is recognized as a key element in grid reliability, it is erroneous to assume that interconnection alone will preclude all grid reliability problems. The 1966 Northeast Blackout originated in Canada (Reference 1) and was made worse by improper protective breaker sequencing. The 1977 New York City Blackout (Reference 1) was caused by lightning strikes on two transmission circuits providing power during a period where there was insufficient in-city generation. Former NRC Chairman Jackson noted in 1998 Senate testimony: “In 1996, two electrical disturbances on the Western Grid caused 190 plants to trip off-line, including several nuclear units. Nuclear plants are designed to withstand unexpected trips. Of course, the nuclear plants themselves are an important element of maintaining electrical network stability.”(Reference 2)

The technical issues associated with the NPP - electrical grid interface include (Reference 3):

- Magnitude and frequency of load rejections, and loss of load to the NPP
- Grid transients involving degraded voltage / frequency
- Complete loss of offsite power to the NPP due to grid disturbances
- NPP unit trip causing a grid disturbance resulting in cascading grid collapse

These are each discussed below in detail.

3.1 Load Rejection and Loss of Load Events

A ***load rejection*** is the sudden reduction in the electric power demand by the grid to supply various consumers. A typical cause for a load rejection is the sudden opening of an inter-tie with a portion of the grid that has a significant load being carried.

A ***loss of load*** would be a 100% load rejection – implying that all external load connected to the output of the plant switchyard is suddenly lost or a major generator output breaker fails open.

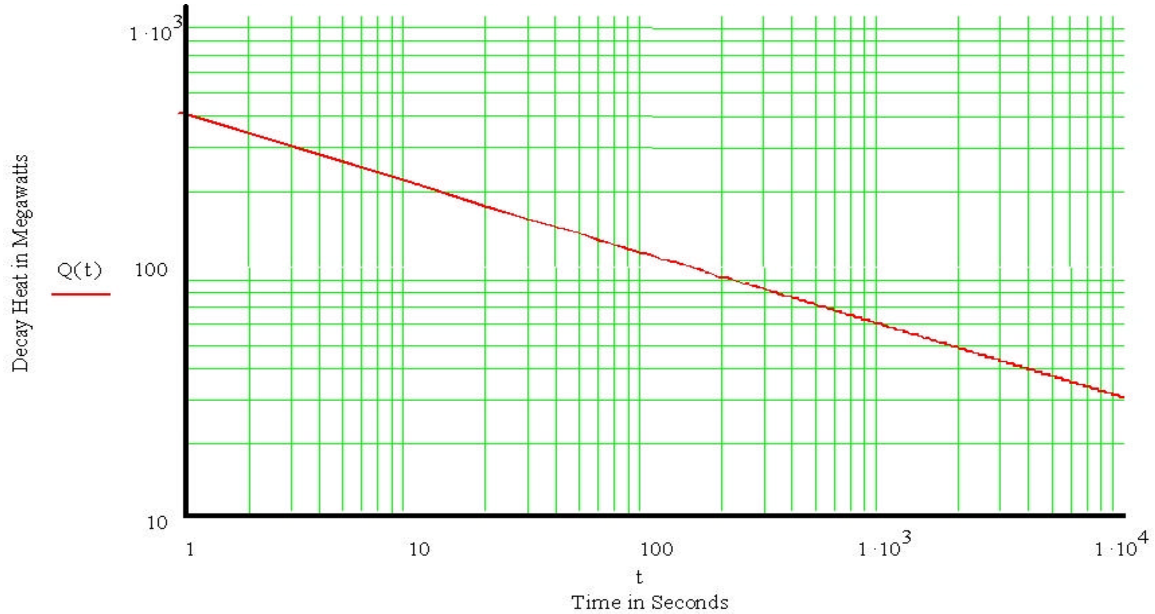

Figure 1

As a grid-related performance feature, NPPs are typically designed to ride-out certain magnitudes of load rejections without tripping the unit. NPPs are primarily designed primarily for base load generation. NPPs have a load rejection capability in the range ~ 50% depending on the reactor and balance of plant design[1] and the ability to load and un-load at about 5%/minute within a specified power band. The key technical problem in coping with sudden load rejection events is in reducing the reactor power quickly without tripping and then being able to quickly increase the power output back to the original value when the fault is cleared.

Reference 4 describes the techniques used on the Combustion Engineering – CE System 80 plant for coping with load rejections. Reference 5 describes the equivalent strategies used in the Westinghouse nuclear power plant. Load rejections in the range up to 50% are accommodated by a combination of: rapidly running back the steam turbine to the new demand level, bypassing a major portion of the excess steam around the turbine to the main condenser unit, and reducing reactor power via insertion of control rods. The load rejection capability of a specific NPP design involves primarily consideration of economic factors such as how much excess sizing should be provided in the main condenser unit to cope with infrequent large load rejections.

3.2 Degraded Voltage/Frequency Events

Electrical grids in developed countries are controlled to assure a set frequency (either 50 Hz or 60 Hz) is maintained within a small tolerance depending on the regional grid standard. When there is an imbalance between generation and load, the grid frequency tends to droop. This can be caused by insufficiency of available generation, a major electrical disturbance such as a fault on a circuit, loss of a major load, or trip of a major generator. Figure 2 shows a simulation taken from Reference 6 of the frequency droop effect caused by the sudden loss of 10% of system generation assuming different settings of automatic regulation.

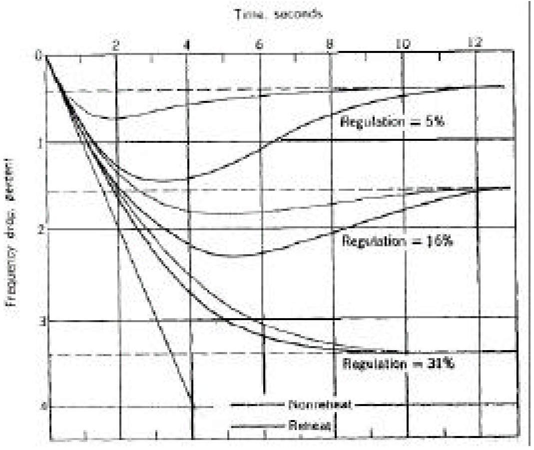

Figure 2

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[1] As noted in Reference 4, some Combustion Engineering NPPs have been designed for 85% and higher load rejection capability.

Power system operators initially attempt to control such small grid frequency droop in such circumstances by adding on more generation (gas turbines or hydroelectric power) to balance the generation vs. demand. If this is not possible, the grid voltage can be reduced (in small stages of ~ 5-10%) in order to maintain frequency. These are what the general public notice as "brown-outs" where the electricity supply is not sufficient to fully illuminate normal lighting. If these measures prove inadequate, further frequency decay can occur and this will lead to grid frequencies requiring major automatic load shedding in order to prevent the grid from collapsing.

Grid voltage decay transients have historically occurred when there was insufficient power system reactance[2] to cope with system disturbances. Reference 1 analyzed an event involving degraded voltage that occurred in July 1976 at the Millstone Nuclear Power Station. Degraded voltage transients have been observed frequently during faulted conditions occurring during periods of low power system demand (such as on weekends when major industrial loads are not present).

The technical concern about degraded grid frequency and voltage lies with the fact that nuclear power plants have normal operating systems (such as main reactor circulating pumps) and long-term decay heat removal systems that rely on stable electric power to function properly. It is well recognized that AC motor performance is directly affected by the voltage and frequency of power supplies to run such motors. If electrical grid voltages are not sufficient, motors cannot develop sufficient motor torque to start.

Figure 3 shown on the following page illustrates the typical starting (upper) performance curve and running curve (lower) for a large AC motor taken from a Russian nuclear power plant cooling system. Note that at the normal 50 Hz the minimum starting voltage would be 82% Nominal. This minimum level decreases until about 48.25 Hz at which point, higher and higher operating voltages are required in order to start and to continue running. If the voltage is insufficient it results in excessive current being drawn by the motor that would lead to opening of protective fuses or protective breakers.

The implication of such curves is that a relatively narrow performance band exists in which large AC motors can be operated. This results in requirements for protection systems in nuclear power plants to trip the reactor and turbine, separate the plant electrical systems from the degraded conditions present on the grid, and rely on DC Batteries and onsite emergency power sources until such time as the grid voltage and frequency are restored to acceptable values.

This type of strategy is focused on protecting the NPP (thus avoiding risk to the public) is used in most countries. This strategy presents problems for countries where an NPP is being deployed in an area with an existing unstable electrical grid. The sudden automatic shutdown of a large base load nuclear unit during periods where there is a mismatch between generation and load can only tend to aggravate the situation.

3.3 Loss of Offsite Power Events

Loss of Offsite Power Events are typically caused (References 3, 7) by external events such as lightning strikes, hurricanes, and transmission line faults that occur beyond the plant switchyard. A loss of offsite power causes the sudden interruption of normal power to all in-plant loads such as pumps, and for most reactor types causes the control rods to insert independent of any control or protective system actions.[3] All nuclear power plants are designed to cope with loss of offsite power by tripping the reactor and turbine, attempting to switch to an alternate offsite power source and if this fails starting emergency onsite diesel generators to provide heat removal until normal power is restored.

3.4 NPP Trip and Cascading Grid Collapse

In a situation where an NPP, carrying a significant portion of the electrical grid, trips this can result in significant imbalance between available generation and load. Unless additional power can be quickly imported via external grid connections or generation added quickly, this can lead to degraded voltage and frequency on the alternate offsite power connections that will result in a loss of offsite power to the NPP.

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[2] Reactance, expressed in MVARs is the power required for charging up the inductive loads (magnetic fields) in all connected loads.

[3] In the RBMK reactor type control rods are held out of the reactor by power sources independent of offsite power.

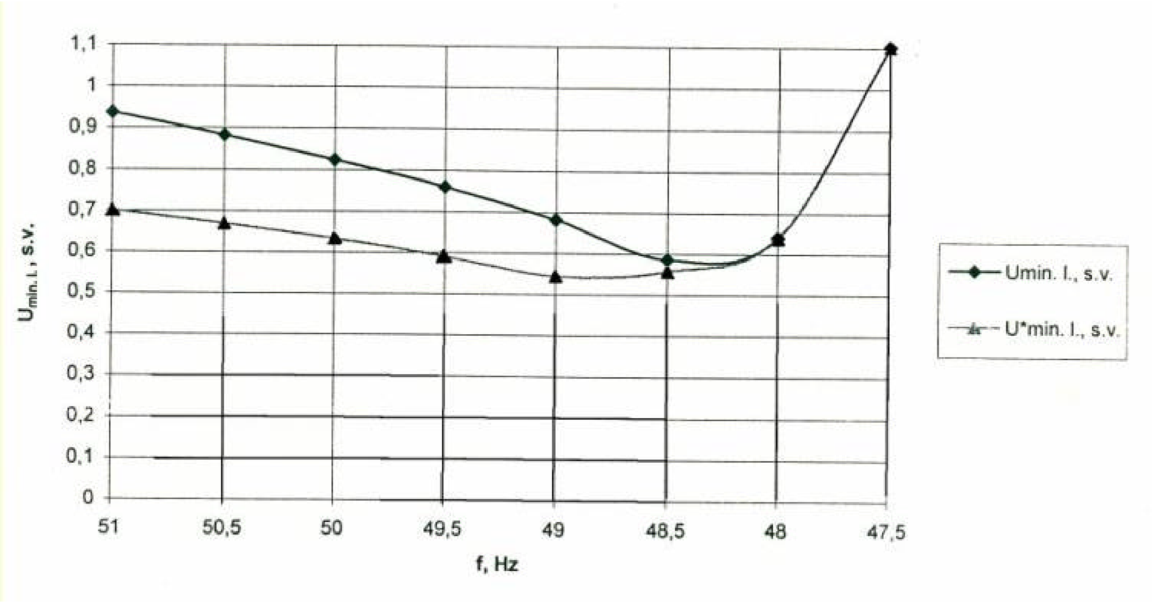

Figure 3
Minimum Starting/Operating Voltages for a Large AC Pump Motor

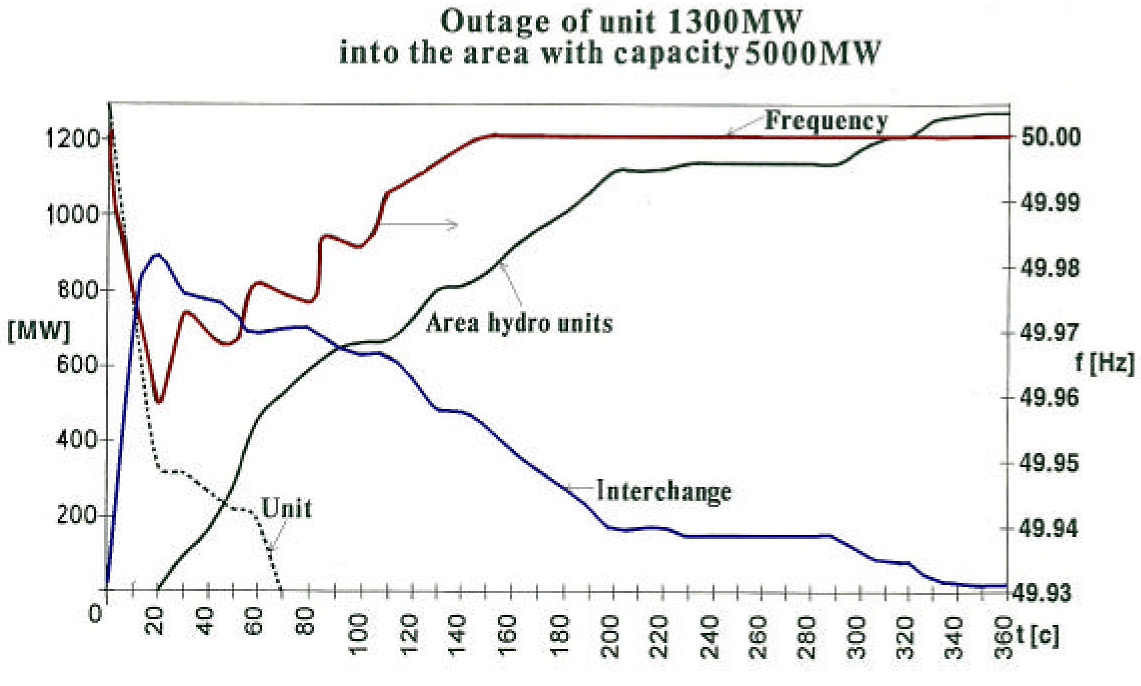

Figure 4

Simulation of the Trip of a 1300 MWe NPP in Lithuania on the Baltic Regional Grid

Figure 4 above shows the desired performance of a grid in which a 1300 MWe NPP suddenly trips. In the short term (first 20 – 30 seconds) only the availability of interchange power prevents the grid from collapsing. Over the longer term, the ability to dispatch hydroelectric power recovers the grid frequency to the nominal 50 Hz.

4.0 Safety Regulations and Standards Dealing with the NPP-Grid Interface

As noted previously in the discussion of safety considerations, the key difference between nuclear and conventional thermal plants is the heat that must be removed following a plant trip. All thermal power plants that are run at elevated temperatures require time to shut off the heat source, (be it from oil or coal combustion) and to cool down metal components without damaging boiler tubes or furnace walls. A nuclear reactor, even with the chain reaction completely shut down, will continue to generate significant heat from fission product decay that persists on a logarithmic time scale as was shown in Figure 1.

The implication of this long-term decay heat curve is that a reliable means of long-term decay heat removal must be required in order to prevent long term overheating of the reactor fuel elements. Typically[4] the decay heat removal process is dependent on availability of a long-term stable source of electric power.

Nuclear safety regulations and standards dealing with the issue of assuring stable long term normal and emergency power supplies have been developed in the USA since the 1960's. These are based on the principle of providing "defense in depth" against scenarios where the NPP is unable to provide long-term core decay heat removal.

The key defense in depth barriers relative to the electrical grid are:

- Siting NPPs on stable electrical grids in order to avoid challenges requiring protective actions
- Provision of an immediately accessible independent power source from the offsite electrical grid,
- Provision of a redundant and reliable onsite power system based on emergency diesel generators or their equivalent.[5]

US Nuclear Regulatory Commission (US NRC) safety and licensing criteria related to electric power are contained in General Design Criteria 17 or GDC-17 (Reference 8). The IAEA developed equivalent international standards (Reference 9) in the NUSS (Nuclear Safety Standards) Standards, which are very similar to those developed by the US Nuclear Regulatory Commission (US NRC). The key requirements of these safety criteria and experience in applying them are summarized below.

4.1 GDC-17 and IAEA Requirements

GDC-17 requires:

"An onsite and offsite electric power system shall be provided to permit functioning of structures, systems, and components important to safety."

This essentially requires that power be available from both offsite sources and from units such as diesel generators, gas turbines, or other types of emergency back-up power. The criteria further stipulates that:

". each system shall provide sufficient capacity and capability to assure:
. specified acceptable fuel design limits and reactor coolant pressure boundary limits are not exceeded, and..
..that the core is cooled and containment integrity and other vital functions maintained in event of postulated accidents."

These requirements are focused on assuring sufficient power to prevent fuel rod damage and long-term overpressure of the coolant system and containment. Furthermore the criteria require that sufficient power be available to run monitoring and control systems (such as heating and ventilating systems) in the plant until power is restored.

Reliability requirements for the onsite power system are specified in terms of independence and redundancy as follows:

"onsite electric power supplies, including the batteries, and onsite electric distribution system, shall have sufficient independence, redundancy, and testability to perform their safety functions assuming a single failure."

The requirements for redundant transmission circuits are as follows:

"Electric power from transmission network to onsite electric distribution system shall be supplied by 2 physically independent circuits (not necessarily on separate right-of-ways) designed and located to minimize likelihood of

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[4] Some NPP's can temporarily rely on self-powered decay heat removal systems. Examples include: Natural Circulation-drive Isolation Condensers in early Boiling Water Reactors, and Steam Driven Auxiliary Feedwater Systems in Pressurized Water Reactors.

[5] Note: Some emergency onsite power systems utilize hydroelectric dams (Oconee Units 1,2,3), or emergency gas turbine generators (Millstone Unit 1).

their simultaneous failure..” “A switchyard common to both circuits is acceptable.”

Figure 5, shown below was taken from IAEA Safety Guide 50-SG-D7. This figure shows a simplified schematic of one typical interface between an NPP and the electrical grid that conforms to GDC-17.[6] The key features are a main generator connected to the grid via the main generator breaker to the plant transformer. Under normal operation, power from the generator is back-fed to redundant electrical auxiliaries via redundant transformers. The electrical auxiliaries powered include: all critical pumps and motors, battery chargers, and safety related instrumentation and control systems.

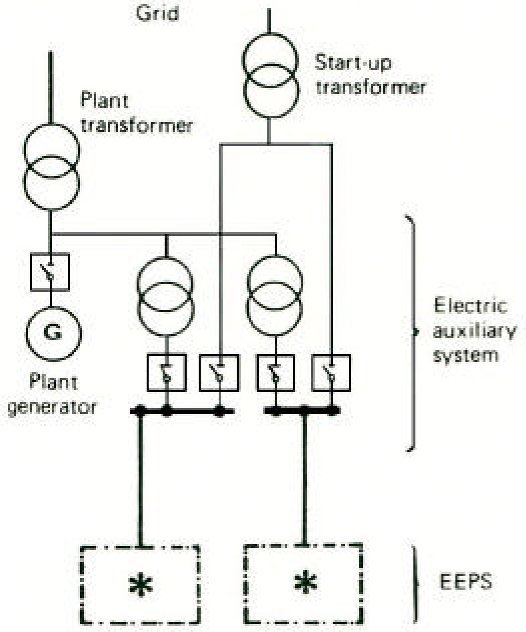

Figure 5
Simplified NPP – Grid Interface

Under the conditions of any plant trip, the first attempt would be to seek offsite power by back feeding from the plant transformer. Should this fail; an attempt is made to seek reliable power from the separate offsite circuit via the start-up transformer – by disconnecting breakers from the primary source and connecting breakers to the secondary circuit pathway. Should this pathway fail, the emergency electric power system (typically comprised of diesel generators) are started and used to energize the safety related station auxiliaries.

4.2 Design Standards and Guidance Documents

The wording of the General Design Criteria described in the previous section is very general in nature. Specific design guidance is found in: IEEE design standards (References 10 – 22), the US NRC Standard Review Plan (Reference 23), and in various US NRC Regulatory Guides and Branch Technical Positions (References 24-32).

The requirement for demonstrating the independence of the offsite transmission circuits is accomplished primarily based on application of physical separation criteria found in standards and other guidance documents.

4.3 Experience from Applying Electric Power System Regulatory Criteria

For the specific situation involving siting an NPP on a large well-interconnected electrical grid, historically the electric power industry’s reliability standards provided sufficient grid reliability for safely operating an NPP.

Reference 25 noted: the US NRC Staff had: “*concluded, from a review of appropriate reliability data, that power systems with supporting grid inter-ties meet the grid availability criterion with some margin. This conclusion is applicable to the review of most plants located on the U.S. mainland”* (and would probably be true on any modern electrical system in any developed country). The US NRC has dealt with electrical grid reliability issues according to a 1981 Branch Technical Position (Reference 25): that requires the US NRC to: *“examine the available generating capacity of a system, including inter-ties if available, to withstand outage of the largest unit. If the available capacity is judged marginal to provide adequate stability of the grid, additional measures should be taken. These may include provisions for additional capability and margin for the onsite power system beyond the normal requirements, or other measures as may be appropriate in a particular case.”* These requirements pretty much mirror those suggested by Power System engineers in the late 1960’s to assure reliable power to the general public and described in Reference 6.

It was recognized that in some scenarios involving a weak, poorly interconnected or coordinated electrical grid – the sudden shutdown of a large NPP might result in the collapse of the overall power grid despite the use of “physically independent connections” to the grid.

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[6] There are numerous ways to design an NPP-Grid interface according to IEEE-Std 765-1983 (Reference20).

This occurred in the preliminary licensing reviews of a proposed NPP to be sited in Puerto Rico in the 1960's where the US NRC noted: *"The staff has traditionally required each applicant to perform stability studies for the electrical transmission grid which would be used to provide the offsite power sources to the plant. The basic requirement is that loss of the largest operating unit on the grid will not result in loss of grid stability and availability of offsite power to the plant under consideration. In some cases, such as plants on the island of Puerto Rico, the plant is connected to an isolated power system of limited generating capacity. <u>These kinds of isolated power systems are inherently less stable than equivalent systems with supporting grid inter-ties. It is also obvious that limited systems are more vulnerable to natural disasters such as tornadoes or hurricanes</u>."*

The design and licensing basis for this plant required that as a minimum the design would need to be upgraded to "include provisions for additional capability and margin for the onsite power system beyond the normal requirements." The intent of such regulatory positions was to compensate for the likely unreliable offsite power system by providing a higher reliability in the onsite power system. This would provide assurance that for an NPP sited on an isolated power system with limited generating capacity that the sudden trip of the NPP itself (or a larger unit elsewhere on the grid) would not result the inability to cool the reactor core.

5.0 Residual Risks Associated with Unreliable Electric Grids

As with any engineered system, the provision of specific design features to cope with grid disturbances and loss of offsite power does not perfectly assure the elimination of all safety risks. There will always some small residual risk that the engineered systems will not perform as designed and this is the subject of Probabilistic Risk Assessments – or PRAs. PRAs from the era of the Reactor Safety Study in the 1970's (Reference 33) to the more recent NUREG-1150 (Reference 34) have continued to show that Station Blackout scenarios – a sequence of events involving loss of offsite power with concurrent failure of the onsite power system (diesels), and delayed recovery of electric power are the dominant contributors to the core damage risk of all types of NPPs. Safety regulators have recognized the sensitivity of NPP risk to grid reliability (Reference 2). During the periods when many NPPs were originally built there were very large capacity margins in existence and it was relatively easy to demonstrate that the trip of the largest unit on the grid would not cause the grid to collapse or otherwise become degraded to the extent decay heat removal systems could not properly operate.

Operating experience in the US has been tracked to ascertain whether these risks are increasing (as a result of the general reductions in reserve generating capacity margins originally assumed when the NPPs were licensed) or decreasing due to the better reliability of onsite power systems. Overall the trend of US NPP plant trips has decreased significantly over the last decade and reliability of onsite power systems has increased. However as a result of electric utility industry restructuring and the lack of addition of significant new generating plants, capacity margins are less. This brought with it the potential for larger cascading grid events.

Steps currently being undertaken by the utility industry at the request of regulators (Reference 35) in the US include:

(1) Providing guidance to utilities on the need for and acceptable techniques available to ensure adequate post-trip voltages;

(2) Establish provisions to log and evaluate unplanned post-trip switchyard voltages to help verify and validate that the intent stated in Item (1) is met;

(3) Determine plant-specific risks of degraded voltage/double sequencing scenarios.

6.0 Recommendations

The operators of electric grids must recognize the performance characteristics assumed by an NPP they are planning to deploy in their country – and assure that the grid is designed and operated accordingly. This is particularly true when a foreign NPP design, which may be more "attuned" to the electric power grid characteristics in the country of origin, is being installed. The standard way this is done is via performing electric power system simulation studies in which the normal operating environments (nominal system loads and generation in terms of MWe and MVARs) are assumed, and single faults (sudden losses of key transmission circuits or generating units) are systematically postulated. The simulations identify the time dependent power system response in terms of voltage and frequency, physical limitations to prevent overloading transmission circuits, and the effects of automatic features such as automatic load shedding and emergency disconnects. Such studies can be used in confirming that physically separate transmission circuits are in fact independent and that the desired first "defense in depth" barrier is maintained.

In the specific situation of an NPP being constructed in an area with an isolated or unstable electrical grid, per the guidance from Reference 25, "provisions should be made for additional capability and margin for the onsite power system beyond the normal requirements, or other measures as may be appropriate in a particular case." This could include: demonstration of the ability of the NPP to respond to a grid disturbance by disconnecting from the grid, and running back to house load without tripping the unit or by a combination of additional redundancy (more diesel generators) or diversity (incorporation of fast start gas turbine engines) in the onsite emergency power system.

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