SEISMIC FUNCTIONALITY OF ESSENTIAL RELAYS IN OPERATING NUCLEAR PLANTS

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The regulatory criteria for licensing of nuclear power plants require that certain safety-related equipment and systems be designed to function during and following a postulated, design basis earthquake. Demonstration of seismic adequacy must be performed and formally documented by shake-table testing, analysis or other specified methods. Since many older, operating nuclear power plants were designed and constructed prior to the issuance of the current seismic qualification criteria, the NRC has questioned whether the seismic adequacy of the essential equipment has been adequately demonstrated and documented. This concern is identified in Unresolved Safety Issue A-46, “Seismic Qualification of Equipment in Operating Nuclear Power Plants”. In response to this concern, a group of affected plant owners, the Seismic Qualification Utility Group (SQUG), with support from the Electric Power Research Institute (EPRI), has undertaken a program to demonstrate the seismic adequacy of essential equipment by the use of actual experience with such equipment in plants which have undergone significant earthquakes and by the use of available seismic qualification data for similar equipment. An important part of this program is the development of data and the methodology for verifying the functionality of electrical relays used in essential circuits needed for plant shutdown during a seismic event. This paper describes this part of the Seismic Qualification Utility Group program. The relay functionality evaluation methodology is being developed under EPRI Project No. RP2849-1.

1. Introduction

In nuclear power plants currently being licensed for operation, the structural adequacy and functionality of important equipment for earthquake loadings are verified prior to equipment installation by extensive shake-table tests which subject the equipment to simulated earthquake excitations in a laboratory environment. Such tests are performed and the results documented in accordance with industry and regulatory standards – a time-consuming and expensive process. Many older, operating nuclear plants were built and licensed many years before the facilities, procedures and standards for this type of seismic qualification were developed. Because of the fact that the seismic qualification of some equipment in operating plants has not been formally demonstrated and documented, the seismic qualification of equipment in operating nuclear plants is identified as a potential safety concern in U.S. Nuclear Regulatory Commission (USNRC) Unresolved Safety Issue (USI) A-46: “Seismic Qualification of Equipment in Operating Nuclear Power Plants” [1]. In response to this concern, a number of nuclear plant owners formed the Seismic Qualification Utility Group (SQUG) to investigate the problem and develop a proposed approach for its resolution. The application of current seismic qualification standards to the older plants (that is, testing of all equipment on shake-tables) was not considered practical – many of the equipment types and models are no longer available and use of installed equipment for testing is clearly not possible. After consideration of the problem and alternative approaches, SQUG undertook a pilot program to determine if actual experience in fossil power plants and other industrial facilities which have undergone significant earthquakes could be used as a basis for evaluating the seismic adequacy of similar equipment in nuclear plants.

The results of the SQUG pilot program [2] showed the feasibility of using earthquake experience data as a means of assessing the seismic ruggedness of a large cross section of standard power plant equipment used in nuclear plants. Further, the SQUG effort also demonstrated that, with a few exceptions, nuclear plant equipment is generally similar to that installed in conventional plants and, when properly anchored, has inherent seismic ruggedness and a demonstrated capabili-
ity to withstand substantial seismic motion without structural damage. The pilot program results were subsequently confirmed by additional data collection and analysis. As a consequence, the USNRC's plan for the resolution of Unresolved Safety Issue (USI) A-46 is based primarily on the use of SQUG-developed seismic experience data.

For most essential equipment in nuclear plants, demonstration of seismic adequacy under USI A-46 will be accomplished by verifying that the equipment is comparable to that in the conventional plants which have successfully withstood significant earthquakes and by assuring that the equipment is properly anchored. In the case of electrical relays, this approach is not sufficient. First, the types of relays used in power plants are many and diverse and are not easily grouped in generic equipment classes (such as horizontal pumps, transformers, etc.). Second, there have been instances of relay malfunction in earthquakes and in seismic shake table tests at acceleration levels which may be near nuclear plant design levels. For these reasons, the Electric Power Research Institute (EPRI) has established a project to develop the methodology for evaluation of relay functionality in operating power plants. This methodology is intended to provide a practical approach which will provide assurance of the seismic adequacy of the essential relays without the need for explicit qualification tests of each of the hundreds of important relays in these plants. The methodology, criteria and technical approach are described herein. The resulting evaluation procedures will be utilized by owners of operating nuclear facilities for plant-specific evaluation of the essential relays in these plants.

The support and assistance of the Electric Power Research Institute (EPRI) and the Seismic Qualification Utility Group (SQUG) in this project is hereby acknowledged.

2. Relay evaluation methodology

The methodology for evaluation of the seismic functionality of relays is based on a two-part screening process. The first part will identify a minimum set of plant systems, and associated electrical relays, which are required to function to maintain the plant in a safe condition during and immediately after an earthquake. This screening process is intended to significantly reduce the number of systems and electrical circuits which are considered essential to plant safety in an earthquake and, therefore, to reduce the number of relay types whose seismic functionality would have to be demonstrated under current licensing criteria. The second part of the evaluation process will provide a technical approach and data base to assess the seismic ruggedness of the essential relay types used in these plants without the need for expensive, type-by-type testing as is the current practice. Taken together, these two screening approaches are expected to make the relay functionality verification under USI A-46 manageable and significantly more cost effective than would be the case under current licensing criteria, while at the same time providing good assurance that the affected plants can safely shut down and maintain safe shutdown conditions during a major earthquake.

The screening processes for (1) identifying those relays whose functions are essential to safe shutdown and (2) assessing their seismic ruggedness are shown schematically in fig. 1 and are described below.

3. Identification of essential relays

The principal steps in the identification of the minimum set of essential relays are as follows:

3.1. Development of safe shutdown criteria

It has been determined as part of the SQUG and NRC effort on USI A-46 that it is not necessary to verify the seismic adequacy of all plant equipment defined as Seismic Class I in NRC Regulatory Guide 1.29. Instead, only those systems, subsystems and components required to bring the plant to a hot, safe shutdown condition and to maintain it in that condition for a minimum of 72 hours are important to assure safety during and after a seismic event. As a result, the scope of the seismic verification is limited to equipment and supporting systems which provide functions necessary to achieve and maintain hot, safe shutdown. Other important criteria which define systems and equipment which are considered essential are as follows:

- The seismic event does not cause a loss of coolant accident (LOCA).
- A LOCA is not postulated to occur simultaneously with or during a seismic event.
- Offsite AC power may be lost during and/or after a seismic event.
- Random failures of active equipment will not be assumed. However, if the system counted on to remove decay heat from the reactor depends on a single component, alternative systems and/or redundancy will be required.

In addition to these general criteria, the following
specific assumptions provide a basis for the relay evaluation:

- Relays (not otherwise seismically qualified) may malfunction during the short period of strong motion during an earthquake. Such malfunction, typically chatter, may result in loss of system function or inadvertent actuation of systems during the strong shaking period. It is also possible that relay malfunction during strong shaking can result in unacceptable seal-in or lock-out of specific circuits which are designed to have this feature. In such cases, operator or other actions to reset or restore such circuits to their original condition are acceptable provided there is sufficient time, awareness and access for the operators to take this action.
Earthquake experience and test data [3] show that typically relays are not structurally damaged during an earthquake. Therefore, with the exception of certain particularly fragile relay types, which will be identified in the screening procedures, it is assumed that relays are not damaged as a result of the earthquake and will be functional after the period of strong shaking.

Relay types to be evaluated under this program include those devices which are provided to cause contact operation in electric control circuits. In general, they fall into three categories as shown in fig. 2. The largest category is designated auxiliary relays. This category typically includes electromechanical, pneumatic timing and solid state relays used for general purpose control, blocking, closing, lock-out, seal-in and other logic or control functions. A second important category includes protective electromechanical and solid state relays whose function is to protect equipment from system faults and other abnormal or dangerous conditions by automatically initiating appropriate control circuit action. Typical protective relays include over-current, and under-voltage relays. The third general category of relays is contactors. A contactor is a heavy duty relay which may carry significant amounts of current. It is distinguished from a circuit breaker such as is used in switchgear in that its contacts are moved by a solenoid-type mechanism rather than by charged springs or other actuating mechanisms.

The foregoing ground rules and assumptions focus the relay evaluation by defining the objectives of the reviews, the relay types to be considered, the failure modes to be assumed and other important criteria.

3.2. Identification of safe shutdown functions

To achieve and maintain safe shutdown conditions during and following an earthquake, a nuclear plant must accomplish each of the following safe shutdown functions:
- Reactor reactivity control
- Reactor coolant pressure control
- Reactor coolant inventory control
- Decay heat removal

In addition, certain instrumentation is required in order to provide the capability to monitor safe shutdown and to verify that these safe shutdown functions are being accomplished.

The specific nuclear plant systems, equipment and instrumentation which are available to provide the above functions differ from plant to plant. However, all will have one or more alternative systems available to accomplish each of these functions. For example, plants typically include reactor shutdown capability by control rod insertion as well as liquid poison injection. All plants contain one or more methods for control of overpressure. Reactor coolant inventory control means the assurance that the reactor core will remain covered with coolant. This requires that numerous systems be...
available to inject water to remove water from the reactor systems. Finally, all plants have systems for removing the residual or decay heat which is generated by the reactor core during and after power operation. The identification of the various systems and equipment available to carry out the required functions— including those systems required to support the essential systems (e.g., electrical power, control, cooling, etc.) and instrumentation— will provide a listing of all of the alternative safe shutdown systems, support systems and instrumentation which are available to accomplish and maintain safe shutdown conditions in a given plant. The process of identifying these major system alternatives for safe shutdown is illustrated in fig. 3.

The resulting list of systems, equipment and the associated electrical power, control and instrumentation systems, will provide a comprehensive list of safe shutdown equipment, including electrical relays, which are available to achieve the safe shutdown functions.

3.3. Identification of essential relays

The list of all of the alternative systems and associated circuits which are available to accomplish the required safe shutdown functions can be further reduced (1) by selecting the specific combination of systems, or safe shutdown “train”, which would actually be used under earthquake conditions; (2) by considering the time during or following the earthquake when the essential functions are needed; and (3) by evaluating the consequences of postulated relay malfunction in these systems. An additional consideration in the identification of essential relays is the possibility of inadvertent actuation of inactive, non-essential equipment as a result of relay malfunction during an earthquake. These areas are discussed below:

(1) Selection of preferred safe shutdown train

Of the alternative systems available to accomplish the various safe shutdown functions, it is possible to designate the specific systems which will be relied upon in a given plant for safe shutdown under the postulated earthquake conditions. This step narrows the list of equipment to a single safe shutdown train or “success path”, with component redundancy where required by the general criteria. The selection of the preferred safe shutdown train (and the one for which the seismic assessment will be performed) will be based on a number of factors, including plant operations considerations (e.g., which systems the operators prefer to use under the anticipated conditions), the seismic ruggedness of the equipment in each of the safe shutdown trains, the access to the equipment for inspection, the availability of prior seismic qualification test results and records, and the likelihood of success in demonstrating the seismic adequacy of the equipment and relays. It is estimated that this screening step will reduce the list of alternative safe shutdown equipment by a factor of two to three.

(2) Consideration of the timing of required functions

The second step in reducing the scope of the electrical relay evaluation involves consideration of the time during and after an earthquake when certain equipment and systems will be called upon to operate. Because of the short duration of an earthquake (less than one minute), many of the functions needed to achieve and maintain safe shutdown in the long term are not needed during the short period of strong motion and many are
not needed for significant periods of time after the earthquake (i.e., for many minutes or even hours). Therefore, not all equipment and systems in the designated safe shutdown train may be essential for purposes of evaluation of relay functionality. The approach for identifying those specific circuits and relays whose functionality is essential during and immediately after an earthquake involves: (1) establishing which safe shutdown functions are needed during the one minute of strong motion and (2) identifying those functions, systems and components which are needed during the first few hours of the recovery period after the earthquake. The set of relays which requires seismic evaluation includes: (1) the relays whose operability is needed during the strong motion period and (2) those relays whose malfunction (e.g., chatter) during the strong motion could make equipment and/or systems unavailable in the recovery period after the earthquake. The determination of the circuits and relays which fall into the latter category is dependent on two factors. First, can relay malfunction cause lock-out or seal-in of a circuit which will make the affected system unavailable? Second, if seal-in or lock-out is likely, is there sufficient time, operator guidance and equipment access available for a trained plant operator to identify the fact that an important system is unavailable because of relay malfunction, to determine how to reset the relays or breakers to restore the system and to take action to do so? Dependence on operator action to restore systems needed well after the earthquake will require that operators have information available to them on circuit status, procedures for restoring such systems and sufficient time – all of which are plant-specific. Given that these conditions are met, it is considered reasonable to expect that plant operators can take action to correct the effects by any earthquake-induced relay malfunction and to restore the affected systems to operation. Experience in fossil power plants which have undergone strong earthquakes suggests that such operator action can be successfully completed, even without specific procedural guidance and training, within one to two hours. This screening step will further reduce the number of circuits and relays whose seismic adequacy must be evaluated.

(3) Evaluation of the consequences of relay malfunction

As a third step, once the list of systems, circuits and relays needed for safe shutdown is narrowed to only those required to function during and immediately after the earthquake, an evaluation will be made of the consequences of relay malfunction in these systems and circuits. This evaluation is comparable to a failure modes and effects analysis and is intended to identify those specific relays whose malfunction is important and those whose malfunction is inconsequential – that is, those relays whose malfunction will not prevent the essential function from occurring, either because of the specific circuit design or the failure logic employed. For example, many control and power systems in nuclear power plants are designed such that component malfunction (including relay malfunction) results in the system failing in a safe manner. The best example of this fail-safe design approach is the circuitry for initiating reactor shutdown, or “scram”. In this case, failure of normally energized relays or their power supplies results in reactor scram, which in the case of an earthquake is the desired safe action. Relays in these essential systems would not be included on the list of essential relays because their malfunction is inconsequential from an earthquake resistance standpoint.

(4) Consideration of inadvertent actuation of non-essential equipment

Finally, the relay functionality screening process needs to consider the possibility and consequences of relay malfunctions which can actuate equipment and systems which are not essential for safe shutdown but whose inadvertent actuation could lead to undesirable or unacceptable consequences. Examples of such consequences could include the inadvertent operation of normally closed and inactive isolation valves in the reactor coolant pressure boundary. Such actuations could lead to unwanted loss of reactor coolant inventory and even overpressurization of low pressure systems. Accordingly, as part of the relay functionality screening process, it is necessary to identify those power and control systems, their associated circuits and relays whose inadvertent actuation should be avoided and to include on the list of essential relays all relays whose actuation could cause the unwanted system actuation.

The functional screening process described above will result in the minimum set of essential electrical relays whose seismic operability must be verified to assure that the plant can be brought to a safe shutdown condition under the criteria established in USN A 46.

4. Assessment of the seismic adequacy of essential relays

Under current design and licensing criteria for nuclear power plants, the designated, safety-related relays would be formally qualified by shake-table tests, most likely in the specific cabinet or panel arrangement in which they will be mounted. Since this is generally
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not practical for older operating plants, and since actual experience with power plants which have undergone strong earthquakes has not shown significant or widespread problems with standard power plant equipment, including most relays, alternatives to formal qualification testing have been developed. These alternatives involve the assimilation and application of available seismic qualification test data and actual earthquake experience data on a wide variety of relay types.

The resulting information on the seismic ruggedness of various relay types, manufacturers and models results in a generic data base which can be used to assess relay functionality in a given nuclear power plant. The development and the use of the generic relay ruggedness data are described below.

4.1. Use of seismic qualification test data

EPRI (through its contractor, ANCO Engineers) has gathered, evaluated, and consolidated available seismic qualification data on a wide variety of types of relays [4]. These data have been reduced to generic seismic ruggedness spectra which define seismic acceleration levels below which relays can be expected to function without chatter or other damage. These bounding spectra are referred to as Generic Equipment Ruggedness Spectra (GERS). The GERS will provide seismic response spectra within which an entire class of relays has functioned properly during formal shake-table qualification tests. In some cases the GERS are based on "success" data (that is, seismic qualification test spectra for which no relay malfunctions occurred). In this case, the test spectra for numerous relays in a given class represent a lower bound of the seismic ruggedness of the class. In other cases, illustrated in fig. 4, the GERS may be based on "fragility" data (that is, seismic response spectra in which failures or malfunctions occurred). In this case, the qualification spectra represent an upper bound of the seismic ruggedness of the relay class. Where both success and fragility data are available for a given relay class, the GERS must obviously fall between the two qualification spectra. Engineering judgement is used in developing the GERS to smooth out sharp peaks and valleys in the test response spectra and to assure conservatism. A composite set of GERS for several relay types is shown in fig. 5.

4.2. Use of seismic experience data

Data on relay performance, specific failures, relay vulnerabilities, and other lessons learned from actual experience in power plants and other facilities which have undergone significant earthquakes have been documented and are currently being evaluated [3]. This information is being used to identify unacceptable relay types (e.g., specific relay types which are known to be susceptible to damage due to moderate shaking), unacceptable mounting arrangements, and similar deficiencies. Unacceptable relays and other vulnerabilities which must be avoided will be listed and considered in the screening procedure. The positive/success data from
ENERGIZED AUXILIARY RELAY (HINGED ARMATURE) GERS IDENTIFICATION

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Fig. 5. GERS for auxiliary relays (energized) (from ref. [4]).

actual earthquake experience may also be utilized as a part of the relay screening procedure to verify the seismic ruggedness of an entire class, or sub-class, of relays up to certain acceleration limits. For example, it is possible that the experience data will demonstrate that certain classes of relays (e.g., energized auxiliary relays) are inherently rugged (both structurally and functionally) and require no further seismic evaluation for nuclear plants in moderate and low seismicity regions of the country (e.g., east of the Rocky Mountains). Finally, the relay experience data provide valuable insights on operator response during actual earthquake conditions.

The generic qualification data are expected to apply to a majority of installed relay types in essential circuits. Plant-specific and relay-specific qualification data, where available, can also be utilized. Essential relays which are not covered by such data, or which are not sufficiently rugged for a specific application, will require corrective action. Such corrective actions will be developed and implemented by SQUG member utilities on a plant-by-plant basis. Alternative corrective actions could include: (1) refinement of initial seismic requirements and/or analysis, (2) testing of the relay and/or cabinet in question, (3) circuit redesign and modification to make relay function nonessential, (4) relocation of relays to reduce seismic demand, (5) replacement with seismically qualified relays, or (6) other approaches.

5. Future plans

The methodology described above for identifying the specific sub-set of safety-related relays which are required to function during an earthquake and for the assessment of their seismic functionality is currently being developed in the form of implementing procedures, guidelines and data as part of EPRI Project NP-2849-1. Following review of the methodology by industry and regulatory groups, the approach will be tested by trial use on two, operating nuclear power plants - one a pressurized water reactor (PWR) and one a boiling water reactor (BWR). Lessons learned in this process will be incorporated and the methodology will be issued for use by utilities in performing their seismic evaluations as part of the resolution of USI A-46.

References