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SEISMIC CAPACITY OF SWITCHGEAR*

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ABSTRACT

As part of a component fragility program sponsored by the USNRC, BNL has collected existing information on the seismic capacity of switchgear assemblies from major manufacturers. Existing seismic test data for both low and medium voltage switchgear assemblies have been evaluated and the generic results are presented in this paper. The failure modes are identified and the corresponding generic lower bound capacity levels are established. The test response spectra have been used as a measure of the test vibration input. The results indicate that relays chatter at a very low input level at the base of the switchgear cabinet. The change of state of devices including relays have been observed. Breaker tripping occurs at a higher vibration level. Although the structural failure of internal elements have been noticed, the overall switchgear cabinet structure withstands a high vibration level.

INTRODUCTION

Under the sponsorship of the United States Nuclear Regulatory Commission (USNRC), Brookhaven National Laboratory (BNL) is evaluating existing test data of nuclear power plant equipment to determine their seismic fragiltiy levels. The methodology being used for the data evaluation was presented at the 1987 Pressure Vessel and Piping (PVP) Conference and its usefulness was illustrated by applying the approach on the preliminary data collected for switchgear and motor control center assemblies [1]. The evaluation technique was further refined to include a probabilistic estimate of the fragility level. The data base was also expanded to incorporate additional test data and further clarification of the existing data for switchgear, motor control center and other equipment. The refined methodology was applied on the comprehensive data base for motor control center, switchboard, panelboard and power supply, and the results were published in NUREG/CR-4659, Vol. 2 [2]. Recently, similar works have been performed on the expanded data base for switchgear and the results are discussed in this paper. Test data of both low and medium voltage switchgear assemblies have been analyzed. The deterministic lower bound seismic level for each important failure mode is presented in terms of the test response spectrum (TRS). The probabilistic results are presented in terms of the median values, the coefficients of variation due to uncertainty (β_u) and randomness (β_r), and the high (95%) confidence of a low (5%) probability of failure (HCLPF) values. The zero period acceleration (ZPA) and the average spectral acceleration (ASA)** are used to represent the input motion. A description of the data base and equipment is included. The failure modes observed in the data base test programs and the modifications to the equipment that improved its seismic resistance are also discussed.

* This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.

** Spectral accelerations were averaged over 4-16Hz.

EQUIPMENT DESCRIPTION

The principal function of switchgear is to safely turn "on" and "off" the power and this is accomplished by means of air circuit breakers in low voltage switchgear and air, magnetic, vacuum or gas circuit breakers in medium voltage switchgear.

Low voltage metal enclosed switchgear assemblies are composed of units that are arranged to suit the user's requirements and are applied on power circuits up through 600 volts. Each unit has three or four compartments which can contain circuit breakers. The low voltage circuit breakers typically incorporate overcurrent trip devices as an integral part of the circuit breakers. An instrument compartment which contains potential transformers, instruments, meters, relays and secondary control devices may also be included. The rear of the unit is allocated for the buses and power cables.

Medium voltage metal-clad switchgear assemblies consist of units with several metal-segregated compartments designed to accomodate medium voltage insulated primary bus bar assemblies, drawout circuit breakers, cables and insulated connections. They also contain low voltage wiring, protective, control and auxiliary equipment. Switchgear equipment having continuous current ratings of up to 3000 amps and short circuit capabilities to 350 MVA at 5 KV and 1000 MVA at 15 KV has been applied in nuclear stations. The three common nominal medium voltage switchgear ratings are 5, 7.5 and 15 KV. Medium voltage circuit breakers do not ordinarily incorporate overcurrent devices and, therefore, require separate protective relays.

Instrument transformers sense the primary voltage and current within the switchgear and accurately transform them to levels required for activation of low voltage and current devices such as instruments, meters and protective relays. The switchgear assembly may accommodate other devices, but the fundamental components such as primary bus conductors, circuit breakers, instrument transformers and wiring are found in practically all metal-clad switchgear assemblies.

DATA BASE

The data base includes multifrequency test results of eight low voltage and thirteen medium voltage switchgear assemblies manufactured by five major companies. The tests were performed in the period 1975-81 following the guidelines of IEEE Std 344 [3]. A description of the data base specimens is provided in Tables 1 and 2. Typically, a switchgear assembly is approximately 90 inches high and 60-100 inches deep. Most test specimens were two to four units (also known as vertical sections, bays or frames), although there was one single-unit and one seven-unit assembly. The specimens were either welded or bolted on the shake table. In a field installation, the switchgear assembly may contain larger numbers of units placed side by side. Many lineups contain more than twenty units.

TEST RESULTS

The fundamental frequency recorded at various locations in the switchgear assemblies for a sine sweep level of 0.2g varies from 2Hz to 16Hz. A lower bound of the fragility TRS levels for low voltage switchgear assemblies is shown in Figure 1. Relays chattered up to 180 milliseconds in a random multifrequency test at a level as low as that depicted by curve 1A. At the level of curve 1B, a breaker failed to close.* Minor structural damage, such as a bent and loose ground connector on the breaker panel and backed out door hinge pins, was observed at the level of curve 1C. Breaking of mounting welds and structural frame angles occurred at the level of curve 1D.

A lower bound of the fragility levels for medium voltage switchgear specimens is shown in Figure 2. Relay chatter occurred almost at all test levels including the sine sweep at 0.2g. Curve 2A shows the lowest random multifrequency TRS available in the data base and relay chatter was observed at this level. A fuse holder became disconnected from the panel and fell down on the floor at the level of 2B. A lower bound of the TRS levels corresponding to tripping (i.e. change of state) of relays, auxiliary switches and breakers is represented by curve 2C. A specimen broke loose on the shake table at the level of curve 2D.

* The horizontal TRS has been reduced to account for the low vertical input which is in this case approximately one-third of the horizontal input. The effective reduction in terms of the ASA is 15%.

DATA EVALUATION

The test data have been evaluated based upon the available information in the test reports and discussions with experts from the manufacturing companies. The results are presented in the following subsections.

Dynamic Amplification

In a switchgear assembly, devices are typically mounted on door panels or other sheet metal elements which exhibit large amplification of the input motion. A peak amplification value as high as 20 was observed in the data base at the fragility level vibration input in the frequency range 4-16Hz [4].

Failure Modes

The failure modes observed in the data base test programs can be enumerated as follows:

a) Relay chatter
b) Relay change of state (tripping)
c) Auxiliary switch change of state (tripping)
d) Breaker malfunction (e.g. tripping)
e) Fuse holder disconnection
f) Minor structural damage - buckling and cracking of cabinet frame, crack in arc chute, crack in instrument panel, deformation of bolt washer, weld crack, device connection breaking loose, door hinge breaking, deformation of wire trough, bolt backing off in arc chute, breaking of bus support bracket, deformation of breaker operating arm
g) Major structural damage - specimen breaking loose on shake table

The significance of relay malfunctions and the causes of breaker tripping are discussed in the following subsections.

Relay Chatter

Relay chatter is a common phenomenon observed in switchgear test programs. It occurred even at the lowest multifrequency random vibration and sine sweep tests. However, whether a relay chatter will cause a problem (e.g. trip the breaker) depends on the function of the relay in a particular system.

During a seismic test program, if all the relays were tested with the switchgear specimen in their appropriate locations and if all the protective devices were electrically connected to the trip elements of the circuit breakers or other circuitry per the design, then the protective devices would be qualified provided they did not initiate an unintended operation or did not fail to initiate an intended operation. However, that is usually not the case. The protective devices are usually separately monitored or sometimes tested as part of a separate seismic test program. Their chatter limit is judged based on a predetermined acceptance level for the circuitry in a specific system or, in the absence thereof, based on a generic acceptance criterion, e.g. 2 milliseconds. Similarly, the auxiliary relays that are housed in the switchgear are judged by their functions and acceptable chatter limits for the respective systems or by a generic acceptance criterion. Chattering of relays responsible only for annunciating functions (such as indicating light, alarm) may be acceptable.

In summary, since relays that are responsible for breaker operation (e.g. tripping) were not necessarily electrically connected to the trip element during seismic testing, the acceptability of relay chatter for not causing breaker malfunction should be based on function of the relay in a specific system or a conservative generic criterion such as 2 milliseconds. This approach was used by the nuclear industry in the application of the data base test programs for qualification of specific plants.

Relay Change of State

Relays were observed to trip (i.e. change electrical state) in the data base test programs. The seal-in coil of the relay would sometimes sustain the change of state. In some cases the chatter and the change of state were initiated by the seal-in contact. As discussed above, if during testing these relays were connected to the trip elements of the breaker, the breaker also would trip. Removal of the seal-in contact from the circuit can, in some cases, eliminate this seismic effect; however, the design of the relay, the durability of its contacts and the reliability of the relay are dependent on the presence of the seal-in contact. Therefore, in most applications, the seal-in contact should not be removed except as a temporary measure.

Breaker Tripping

The power circuit breaker accomplishes the principal function of closing and opening the power contacts, thereby applying and removing power to a load circuit. The closing and opening (i.e. tripping) controls on the circuit breaker are momentarily energized and the primary contacts are mechanicallylatched into the closed and open positions. The safety functions of a circuit breaker, a simple two state device, are as follows:

a) Remain closed
b) Open on command
c) Remain open
d) Close on command
e) Any combination (of the above four)
f) Any combination with added critical timing requirements

In addition to the relay malfunctions discussed in the previous subsections, the conditions and arrangements that have been found likely to initiate a breaker malfunction are as follows:

a) The mechanical integrity of the racking mechanism with regard to holding the circuit breaker in the connected position
b) The electrical performance of stationary breaker auxiliary contacts (switches) which, since they are mounted on the cabinet but operated by the breaker, monitor the relative locations of the breaker and the cabinet
c) The electrical and possibly the mechanical integrity of power and control disconnect devices which interface between stationary and moving connections for circuit breakers, switches and voltage or control power transformer disconnects.

The specific design establishes the likelihood of having a malfunction at these interfaces. The fundamental cause is the relative motion between the moving element and the frame, driven by seismic vibration. All designs of switchgear are vulnerable to these problems to some extent depending on the integrity of the disconnects and racking or locking mechanism and tolerances designed into the interface. Where breakers insert horizontally and rely on the floor for support, improper floor preparation can affect alignment and increase the likelihood of a malfunction. If frame mounted rails or lift mechanisms are used, the strength and tolerances of the structure, mechanisms and latches affect the fragility level.

Frequently, the circuit breaker and its enclosure respond differently to vibration and cause out-of-phase displacement situations which stress all interfaces between the enclosure and the breaker. At a relatively high acceleration level, this condition will cause mechanical damage.

As will be discussed in the subsequent section, structural modifications were made on both earlier and later products to reduce the effects of the above phenomenon and thus reduce the likelihood of breaker trip and/or damage.

Fragility Estimates

Based upon the test results discussed above, the failure modes have been categorized as follows for the purposes of fragility estimates:

a) Relay chatter
b) Relay and switch change of state
c) Internal damage
d) Breaker malfunction
e) Cabinet structural damage

In item d), breaker malfunction corresponds to either tripping or failure to close. The breaker malfunction data set does not include the relay chatter or the relay and switch change of state data. However, the breaker function could have been compromised if during testing the devices were always electrically connected with the trip elements to simulate the in-service conditions as discussed in the previous sections. Typically, the power circuit breakers are seismically strong and it is the controlling devices that cause the breaker malfunction. Instances of breaker tripping in the data base were attributed to relay malfunctions. However, for one switchgear specimen the failure of the breaker to close was attributed to the binding of the closing mechanism. Internal damage data include test results related to disconnection of a fuse holder and breaking of a transformer support.

For the low voltage switchgear, the available fragility data for individual failure modes have been considered inadequate for performing statistical analysis. The fragility parameters (i.e. the median, uncertainty coefficient and randomness coefficient) have been estimated by judgment based on the data and the HCLPF values have been computed by use of these parametric values. The results are shown in Table 3.

For the medium voltage switchgear, the fragility data base has been considered adequate for performing statistical analysis for the relay contact chatter, the relay and switch change of state and the breaker tripping failure modes. The method of moments was employed for estimation of the fragility parameters. The fragility parameters for the internal damage and the overall structural damage of the switchgear, on the other hand, have been estimated by judgment based on the respective limited data available in the data base. The fragility parameters and the HCLPF values are presented in Table 4.

EQUIPMENT IMPROVEMENT

Changes were made in switchgear designs at different times for different reasons whether these were for improvement of the arc controlling mechanism or due to development of better insulating materials or need for a seismically designed product. The switchgear products manufactured in the 1960's and early 1970's are expected to demonstrate a reasonable amount of seismic resistance. Products made after that time are expected to perform better due to the modifications incorporated with a view to meeting stiffer seismic criteria and higher demands. Since BNL's data base covers test data generated only in the late 1970's, the results presented in this report are applicable for the modified equipment. The details of the early modifications were not available to BNL; however, some of the specific types of later modifications are as follows:

- o Breaker racking and positioning mechanisms were improved.
- o Anchor bolt hole reinforcements or heavier members were introduced.
- o Better subassembly welding was introduced.
- o Mountings of coils, latches, switches etc. were modified.
- o Members were added to panels to reduce local flexibility.
- o Device substitutions were made.
- o Structural members were strengthened.
- o Welding became the preferred method of anchorage.
- o Positioning materials were added to reduce displacements of vulnerable components.
- o Requirement of bolt torquing was introduced.

Available documents indicate that some of the above modifications were needed directly or indirectly for proper functioning and qualification of the breaker, and other modifications were made to improve overall structural resistance and capability.

Modifications continued through the 1970's and further modifications were made generically or for specific applications as a result of test programs, some of which were used in the BNL study. Therefore, it is emphasized that the products specifically qualified and supplied since the tests in the data base are expected to perform significantly better in a seismic environment than the picture depicted by the generic results presented above.

LIMITATIONS

Due to the limitations of the data base and possible earlier modifications, the fragility results presented above are applicable provided the following limitations are satisfied:

- o The switchgear is manufactured after 1975.
- o The equipment rating and configurations are enveloped by that presented in this paper.
- o Since some relay models are known to be very weak in seismic environments, such relays should be carefully screened.
- o The equipment is installed in the field in accordance with the testing as discussed in this paper. Uneven floor preparation increases the likelihood of problems where breakers insert horizontally and rely on the floor for support.
- o The switchgear is in the operating (i.e. connected) position only.

CONCLUSIONS

The data base indicates that the fragility level corresponding to the relay chatter failure mode is low. This does not mean that a switchgear qualified based on the test results of the data base has a low seismic capacity. On the contrary, results of the test program similar to those in the data base were used to characterize a standard product and then, with that knowledge, evaluations were made for specific applications. For example, the specific systems were analyzed for determination of the acceptable chatter limit, relays were relocated within the cabinet, devices were replaced with seismically stronger ones, device mounting and instrument panels were improved, cabinet structure was stiffened and/or strengthened. As a result, although the qualification of a switch-gear for a specific application was derived from the results of test programs similar to those in the data base, the seismic capacity of such equipment used in a specific application is expected to be significantly higher than that depicted by the results presented in this paper, provided aseismic qualification program was implemented for that application.

On the other hand, in order to improve the seismic capacity, modifications were made to the standard products in the period 1968-76. Since the data base test programs were conducted after this period, the "generic" fragility results presented above may be larger than the actual fragility levels for certain earlier products, and should be carefully used for these products. However, since with increasing vibration levels breaker malfunction is first caused by malfunction of controlling devices, replacement of certain weak devices may significantly improve the seismic capacity of early vintage switchgear.

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TABLE 1
Test Specimens - Low Voltage Switchgear

No. of Vertical Sections	Size W x D x H (inches)	Approximate Weight (lbs)	Test Mounting
2	42 x 73 x 94	3400	12 bolt
-	60(D) x 93(H)	-	weld
2	44 x 58 x 90	-	weld
3	65 x 60 x 94	-	weld
7	226 x 68 x 90	15000	weld
-	108(W) x 60(D)	8400	bolt
3	66 x 58 x 90	3600	weld
2	52 x 68 x 90	6000	weld

TABLE 2
Test Specimens - Medium Voltage Switchgear

No. of Vertical Sections	Size W x D x H (inches)	Approximate Weight (lbs)	Test Mounting
2	72 x 97 x 91	8300	12 bolts
3	108 x 98 x 90	10300	-
4	104 x 83 x 90	8000	weld
3	-	-	weld
2	52 x 62 x 90	6800	-
2	72 x 88 x 90	10000	bolts
1	-	-	4 bolts
3	108(W) x 104(D)	15800	20 bolts
4	104 x 66 x 90	8000	weld
2	-	-	bolts
3	98 x 66 x 90	7600	weld
2	90(H)	-	14 bolts
3	108 x 91 x 90	8000	weld

TABLE 3
Fragility Results - Low Voltage Switchgear[1,2]

Failure Mode	Indicator	Median in "g"	β_u*	β_r*	HCLPF in "g"
Relay Chatter[3]	ZPA	1.0	0.30	0.10	0.5
	ASA @ 2%	1.9	0.30	0.10	1.0
Breaker Malfunction[4]	ZPA	1.5	0.30	0.10	0.8
	ASA @ 2%	6.6	0.30	0.10	3.4
Structural Damage	ZPA	3.5	0.15	0.06	2.5
	ASA @ 2%	8.5	0.15	0.06	6.0

1. The acceleration levels are measured at the base of the equipment.
2. The results are applicable only within the limitations discussed in this paper.
3. Relay chatter can cause breaker tripping.
4. Consequences of malfunction of separately monitored controlling devices were not included (see item 3 above).

* Based on judgment.

TABLE 4
Fragility Results - Medium Voltage Switchgear[1,2]

Failure Mode	Indicator	Median in "g"	β_u	β_r	HCLPF in "g"
Relay Chatter[3]	ZPA	0.6	0.44	0.10*	0.2
	ASA @ 2%	1.8	0.49	0.10*	0.7
Relay and Switch Change of State[3]	ZPA	1.4	0.17	0.06	1.0
	ASA @ 2%	3.9	0.11	0.08	2.9
Internal Damage[4]	ASA @ 2%	4.0*	0.10*	0.10*	2.9
Breaker Trip[5]	ZPA	2.0	0.10*	0.10*	1.4
	ASA @ 2%	6.3	0.10*	0.10*	4.5
Cabinet Structural Damage	ZPA	3.5*	0.15*	0.06*	2.5
	ASA @ 2%	8.5*	0.15*	0.06*	6.0

1. The acceleration levels are measured at the base of the equipment.
2. The results are applicable only within the limitations discussed in this paper.
3. Relay chatter and relay and switch change of state can cause breaker tripping. In the data base test programs, these devices were not necessarily connected to the trip elements of the breaker to simulate inservice conditions (see discussion in the text).
4. Internal damage includes disconnection of a fuse holder and breaking of a transformer support.
5. Consequences of malfunction of separately monitored controlling devices were not included (see item 3 above). One additional data point corresponding to breaker malfunction is being investigated and is currently not included in this analysis.

* By judgment.

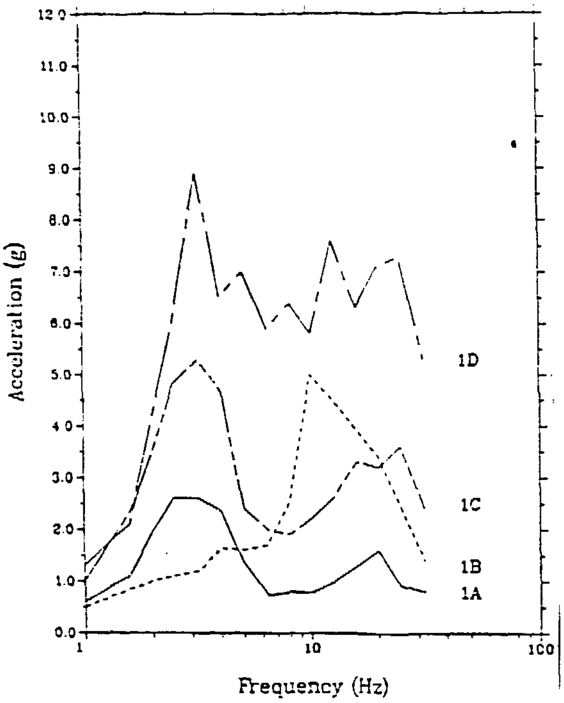

Figure 1 Horizontal TRS @ 2% Damping - Low Voltage Switchgear

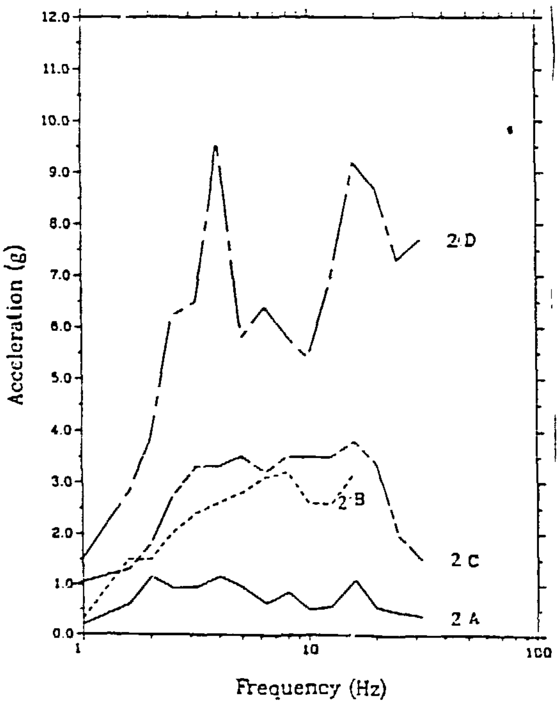

Figure 2 Horizontal TRS @ 2% Damping - Medium Voltage Switchgear