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Seismic Studies: Guide to Measuring As-Installed Frequencies and Damping of Transformer Bushings and Other Substation Equipment

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ABSTRACT

This technical update describes the equipment and procedures for measuring the response of an as-installed transformer bushing using a Man-Shake test sequence. It also provides an example of data analysis to determine the first natural frequency and estimate the equivalent viscous damping using an Excel worksheet. The as-installed frequency of the bushing can also be used to estimate the terminal deflection. This information is needed to determine required conductor slack. The procedures can also be applied to other substation equipment, such as instrument transformers, to determine actual as-installed frequencies from which terminal deflections can be determined; information needed to provide the slack required in flexible conductors connected to the equipment.

Keywords

Bushings
Testing bushings
Bushing frequencies
Bushing damping
Substations
Seismic testing

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1

BACKGROUND

The revision of Standard IEEE 693-2005, IEEE Recommended Practice for Seismic Design of Substations, is in the final approval stages and should be published in 2018. This revision will correct one of the major deficiencies of the existing procedure to qualify transformer bushings operating at 166 kV and above by shake-table testing. This was accomplished by extending, if needed, the plateau of the Required Response Spectrum (RRS) to the stiff-mounted frequency of the bushing being qualified.

Appendix A shows the RRS specified in IEEE 693-2005. The problem with the existing procedure, which primarily affects bushings above 166 kV and below 500 kV, is that the bushings are tested on stiff support structures. For example, a 230 kV porcelain bushing tested on a reasonably stiff support structure had a measured frequency of 20 Hz. When tested on a shake table, the spectral acceleration at the stiff-mounted frequency of 20 Hz is well above the upper frequency of the RRS plateau (8 Hz) and the spectral acceleration to which it is exposed will be about 0.74g. The plateau of a 0.5g 2% RRS has a spectral acceleration of 1.62g. When installed on a transformer, the bushing could have an as-installed frequency below 8 Hz, so the spectral acceleration exposure could be 2.29 times higher than the value to which it was qualified. There are other significant changes to the qualification procedure that are briefly discussed in the Appendix.

Unfortunately, another major deficiency of the existing and revised procedure, in the view of most dynamic specialists on the IEEE 693 Working Group, is that it does not address the bushing-transformer qualification as a system process. That is, it does not consider the effect of the bushing support structure support (i.e., the transformer) on the bushing dynamic response. The as-installed bushing frequency is largely controlled by the stiffness of the transformer tank cover design supporting the bushing. Other factors that affect the as-installed bushing frequency include the location of the bushing on the cover, the height and diameter of the turret, and the locations of cover stiffeners. The stiffeners, usually installed under the cover, are installed to prevent excessive cover deformations when a vacuum is drawn during the bushing installation process, but the stiffeners can also affect the bushing as-installed frequencies and modes of vibration. In addition, the transformer and its appendages can also have other system resonances that can excite the bushings.

Factors in the transformer system that can affect the bushing response are the following:

- The tank has transverse modes, which, if close to the as-installed frequency of the bushing, will cause a large resonance-on-resonance response. This is illustrated with test data discussed below.
- The transformer core assembly has lateral restraints on the base plate to prevent lateral slipping of the core on the base plate, but the core assembly is typically not mechanically anchored to the base plate. There are typically two large horizontal structural members that sandwich the core, core clamps, at the top and bottom of the core. These members are bolted to the core and compress it and extend beyond the ends of the footprint of the core assembly.

The ends of these core clamps at one end of the core assembly are restrained to the end wall of the tank. The other ends are restrained to the other end of the tank or transverse beams that span the width of the tank. An alternative approach is to brace the upper core clamps to the transformer cover. The net result is that transverse mode of the massive core assembly can induce a transverse resonance to the tank. In a detailed dynamic finite element model of a 3-phase 230 kV transformer, the transverse frequency of the core assembly was observed to be 6 Hz, which could be close to the as-installed frequency of the bushings.

- Massive radiator assemblies supported on the tank walls can also impart lateral resonance to the tank and lower the tank's transverse resonant frequency.
- The conservator, if used, is a massive element supported above the tank and partially secured to the tank near the cover. It can also impart a resonance to the system.
- One method frequently used for supporting 230 kV surge arresters consists of two horizontal beams attached to the cover between the A and B and B and C bushings that extend over the side of the tank. These beams support a horizontal longitudinal beam, which supports three surge arresters. In the finite element model referred to above, it was the vertical response of the surge arrester supports that generated the largest earthquake induced base moments to the bushings.
- The high-voltage bushings can be coupled and interact with each other.

2

REASONS FOR MEASURING BUSHING FREQUENCIES AND DAMPING

As noted above, the revision of IEEE 693, when it becomes available, does not address the effect of the transformer on the bushings' dynamic response. The IEEE 693 Working Group agreed to address this important issue in the next revision of the standard, which was to start shortly after the current revision is issued. Thus, when the current revised standard is issued, there will be no requirement for the measurements suggested in this report. However, there are some advantages to making these measurements if the opportunity becomes available. (e.g., when a utility installs a replacement bushing, a new transformer, or when a manufacturer is doing the final electrical test of the dressed transformer). Once personnel are located at the top of the bushing, the suggested test will take about five minute per bushing and the needed skills for testing and data analysis are provided in this guide. The analysis of the data by an engineer should take less than a half hour using an Excel worksheet procedure described in the report.

A poll of the utilities participating in the Seismic Study Group (EPRI) revealed that all of their recent transformer qualification reports used static finite element models of the transformer as part of the qualification process. Discussion with a consultant who does these types of qualifications indicated that on an experimental basis they have done dynamic models of transformers. It was indicated that the effort to convert a static model to a dynamic model does not take much time, however, a good representation of the bushing would be required.

There are several reasons for doing this evaluation even though it is not required, given the minimal effort involved.

- This data provides a method to evaluate the accuracy of the transformer finite element model. While the test frequency is expected to be different from the calculated frequency from the model, a very large difference would indicate that that the model could be improved. This information provides feedback to the modeler so that modeling methods can be improved over time. Just because someone has been modeling transformers for a long time, without feedback there is no way to improve model accuracy.
- Modeling may identify unexpected responses that are undesirable, such as bushing interactions. As noted above, in the model of a 3-phase 230 kV transformer the response of the surge arrester contributed to the bushings seismic exposure. Thus, the model can help the transformer designer to prove the system earthquake performance. The proposed tests would be done as a new transformer is being installed or when a new transformer is ready to be shipped and remediation would not generally be expected, but it can provide information to improve the design of future transformers.
- Gaining a better understanding of the interaction of the bushings and their support structure could improve transformer design and ease the transition to the standard that will probably require this type of evaluation.
- When installing equipment in a substation, the qualification test data is typically used to determine the terminal deflection, which is used to determine the needed slack in flexible

conductors. Bushings are qualified on a stiff support structure so that the bushing's frequency is close to its rigid-mounted frequency. For a 230 kV porcelain bushing frequently used in the United States, the stiff-mounted frequency has been measured at 20 Hz. An as-installed 230 kV bushing has been measured below 5 Hz. The ratio is 4 to 1. The deflection varies as one over the frequency squared, so the qualification terminal deflection can be off by a factor of 16 when compared to the as-installed terminal deflection.

3

FULL-SCALE SHAKE TABLE TEST OF 550 KV TRANSFORMER

Research conducted under the Pacific Earthquake Engineering Research Center (Matt 2003), University of California, Berkeley, explored the dynamic response of several transformers using dynamic finite element models.[1] As part of this effort researchers tested a transformer tank with a simulated 500 kV bushing to validate one of their models. Figure 3-1 from the PEER report shows a schematic drawing of the transformer with instrumentation that was used. The unit was mounted on a 1-degree of freedom shake table. It was subjected to a .25g Landers earthquake. The amplitude of the excitation was limited because of large overturning moments. The tank was 20 feet tall. The accelerometer used to determine the test response spectra was in the upper corner of the end face of the tank. This avoided recording the out-of-plane resonant response of the tank wall. Note that the bushing is installed near the corner of the cover. Research at MCEER, Buffalo, of bushings in the corner of a simulated transformer cover show that the modes of vibration of bushings tend to be into the corner and perpendicular to this direction rather than in the longitudinal and transverse directions, although stiffeners under the cover can change this. The modal frequency into the corner is lower than its orthogonal modal frequency.

A fully dressed transformer would be too heavy for most shake tables, which are typically limited to about 40,000 pound load. The unit tested had no core, oil, radiators or conservator. Welds around the base of the tank anchored the unit to a support frame. Figure 3-2 shows the longitudinal test response spectrum for a Landers earthquake. Several features of this plot are of interest. As noted above, corner mounted bushings typically have modes of vibration skewed from the principal directions. The longitudinal excitation will excite both horizontal modes. The bushing was designed to have an installed frequency of about 3 Hz. The lower as-installed bushing frequency would be into the corner of the tank. The response of the bushing response actually excited the tank, where the measurement was made. The most striking feature of the plot is the longitudinal tank frequency of 6.74 Hz and its amplification of over 8 (6.25% damping). In developing models of equipment it is very difficult to determine the proper system damping, as this requires test data, unless supplemental dampers are added where there damping characteristics are known and can be incorporated into the model. Had the bushing had an as-installed frequency near the tank resonant response, the bushing would have experienced an amplification of about 8, however, the bushing was qualified on the assumption that the tank amplification at the bushing as-install frequency would not exceed 2. Thus, in this earthquake the bushing would have experienced an excitation four times larger than in its qualification test.

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[1] The report can be downloaded free from the PEER website Publications, Research Digest (2002-2006), Lifelines before 2006, Seismic Performance of Substation Equipment, “406 Seismic Qualification Requirements for Transformer Bushings”.

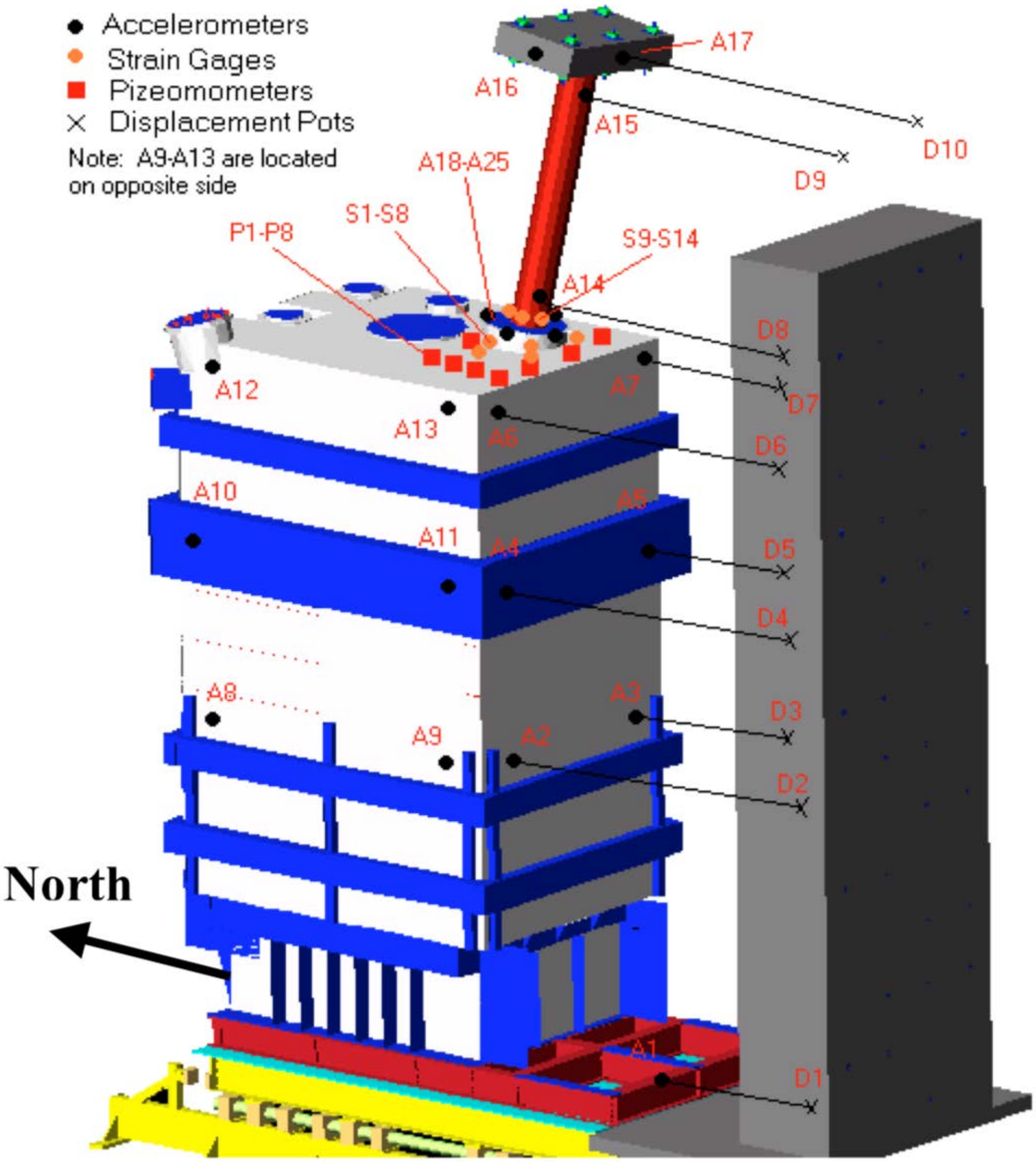


Figure 3-1
Schematic drawing of 550 kV transformer tank and simulated bushing

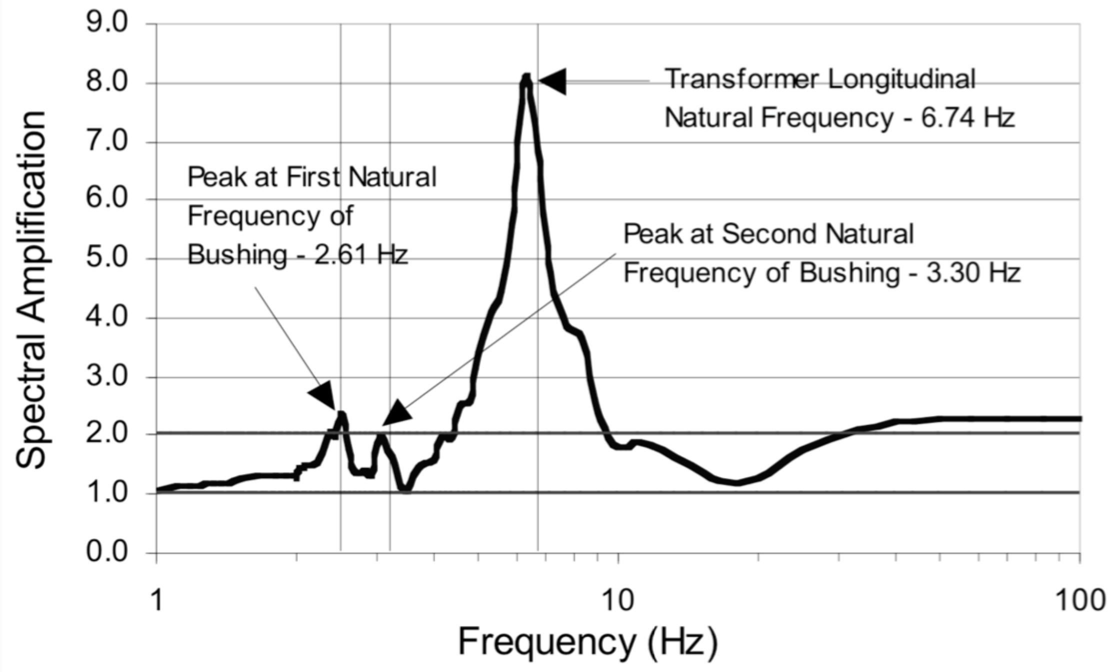


Figure 3-2
Test response spectrum from Landers .25g earthquake

In the IEEE 693 Working Group an alternative proposal was made to design the transformer tank so that the as-install bushing frequency would be at least ¾ of its stiff-mounted frequency. Older 500 kV porcelain bushings typically have stiff-mounted frequencies in the range of 6 Hz to slightly over 8 Hz. Increasing the as-installed bushing frequency will tend to reduce the base moment that the bushing experiences, other factors not considered. However, without knowledge of the transformer dynamics this could be disastrous in this situation, as it would bring the as-installed bushing frequency near the tank resonant frequency. Generally, stiffening the cover to increase the as-installed frequency of the bushing would have little effect on the tank frequency transverse frequencies.

It was noted that this test was not of a dressed transformer, as it lacked oil, core, radiators and conservator. The addition of oil will add significant weight that the tank will have to resist from lateral earthquake excitation, and it does not add to the tank stiffness. The oil could add damping to the system (reduce the amplification), but for a transformer with a conservator, the tank is full of oil and the static deflection (deflection from a constant 1g transverse acceleration) of the inertial centroid of the tank would only be .22 inches at 6.74 Hz system. It is felt that the oil would move with the tank and not significantly contribute to the damping of this mode of vibration. This system also lacks the weight of the radiators, conservator, and core that would also lower the system frequency. A transformer of this size would probably be anchored at 6 to 8 locations, but this tank was welded around the entire base, so a realistic anchorage would also lower the system frequency slightly.

4

HARDWARE FOR TESTING

We have used an accelerometer assembly (x2-2) manufactured by Gulf Coast Data Concepts. Each assembly consists of three accelerometers, each orientated along orthogonal axes with each having a full-scale acceleration capacity of +/- 2g. The resolution of each accelerometer is about 15 bits, which defines 32,768 steps, thus, there are 16,384 steps for the positive and negative accelerations. Thus, the resolution for a 2g acceleration is about .0001g. For most applications this is adequate. The sample rate used was set at 128 samples per second (sps); higher rates of 256 sps and 512 sps are also available. Higher samples rates generate longer files that are more time consuming to analyze using Excel. Each assembly contains a rechargeable battery, analog to digital converter, digital memory to store the data, a USB connection to connect to a computer to download data, and an off-on switch. The data has a Comma Separated Values (.csv) format, which can be opened in Excel. The unit stores the output of the accelerometers in files, where a new file is established by turning the unit on and off. This file is divided in segments of selectable size. I use 30,000 samples per channel per file segment, as some older Excel software can be limited to 32,000 lines per column. The "config.txt file, which can be changed, controls the gain, sample rate, and file size. The data is stored in whole number format and must be divided by 6554 to convert it to g values. The internal battery can be charged via the USB computer connection. The battery life is good for a day's work. The cost is about $150. I have no affiliation with the company and other instrument sources may be available. Figure 4-1 shows a diagram of a unit in which the axes are defined. The unit size is about 1 x 1 x 4 inches.

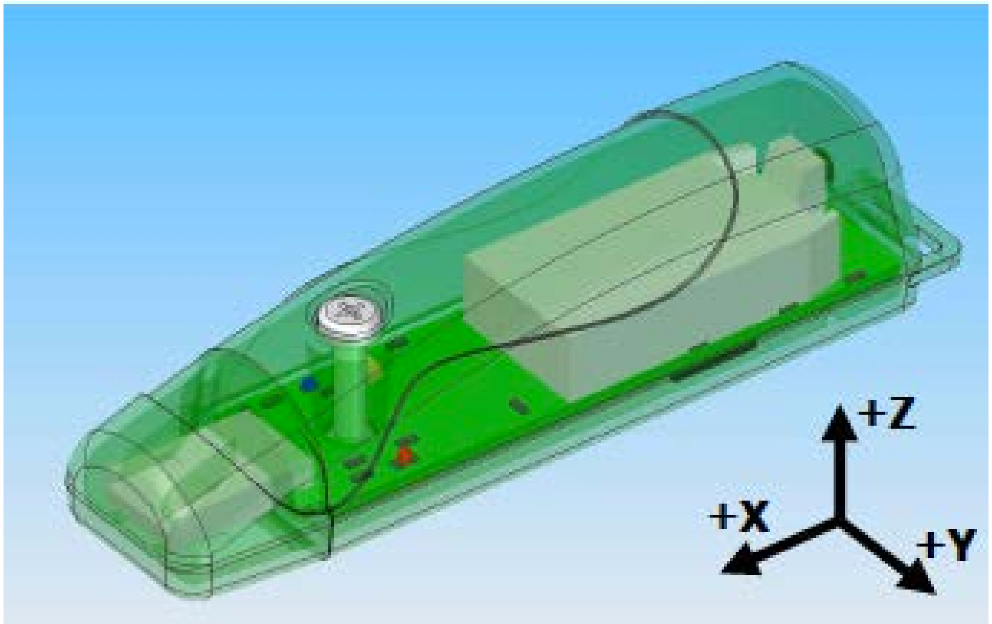


Figure 4-1
Schematic drawing of accelerometer and designation of axes

Figure 4-2 show an accelerometer that has been modified to facilitate attachment to the equipment to be tested by adding a magnet to its base. Originally a wooden block was used to separate the accelerometer from the strong rare-earth magnet, but this separation was not needed. Instead, the block serves another purpose. The accelerometer is hot-glued to the wood block and the magnet (available from Harbor Freight or Home Depot) has a hole in the center and is screwed to the block. Without the wood block, gripping the accelerometer assembly to removing the assembly from the test item can break the hot-glue connection. To remove the accelerometer from a test item, the wood block is gripped rather than the accelerometer assembly. The face of the magnet is covered with tape to prevent steel files from clogging the magnet.

Figure 4-2
Accelerometer glued to wooden block with magnet screwed to block

Figure 4-3 shows a woodshop clamp (available from Home Depot) that has been modified to facilitate attaching the accelerometers to bushings, as magnetic materials are seldom present at the top of the bushing. The accelerometers can be used to test many types of substation equipment where the clamp is not needed. The clamp can be attached to the terminal stud or other hardware at the top of the bushing. A bent plate has been bolted to the clamp by drilling a hole through the clamp jaw, but is allowed to twist. A felt pad, used to protect floors from scratches by chair legs, prevents the clamp from scratching the equipment and provides a grip that is less likely to slip. The string with the spring clip is used as a safety strap to restrain the unit should it slip off the item to which it is clamped.

Figure 4-3
Workshop clamp modified to mount accelerometer to non-magnetic materials

Figure 4-4 shows an accelerometer attached to the 500 kV bushing conductor post on a transformer that was taken out of service for replacement. Note that the clamping device has been modified so that the angle supporting the accelerometer is now stiffer.

Figure 4-4
Accelerometer attached to 500 kV transformer bushing that is being replaced

5

MAN-SHAKE TEST SEQUENCE

The so-called man-shake test sequence consists of three separate excitations used to assess the frequencies and damping of the modes of the bushing in one direction:

- Sine sweep test
- Hand impact test
- Rubber mallet test

Figure 5-1 shows a bushing response to a man-shake sequence. Testing is usually done from a man-lift to get access to the top of the bushing.

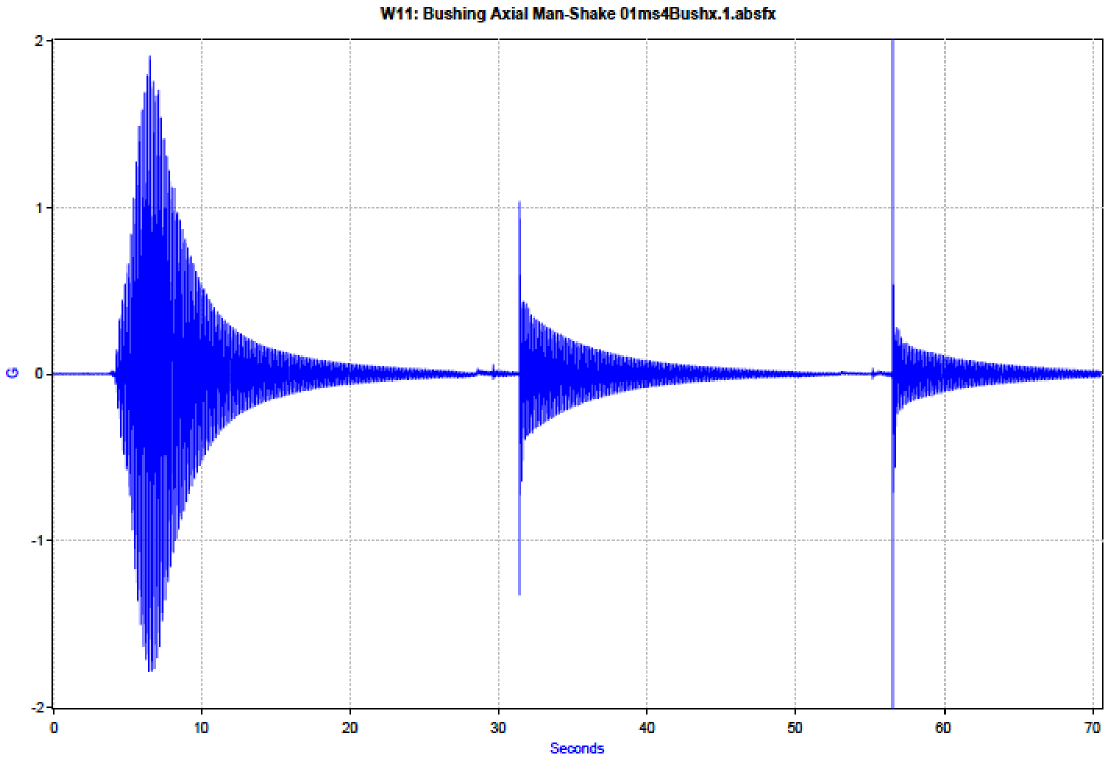


Figure 5-1
Man-shake response sequence of a 230 kV bushing in the one direction

Sine Sweep Test

Grab the bushing and shake it with a sine-sweep excitation in the direction of an anticipated mode of vibration. That is, start at low frequency and increase the frequency until resonance is reached. Continue shaking at the resonant frequency to increase the amplitude of the bushing response. When an acceptable response is achieved, release the bushing and let it ring down. It is possible to generate response acceleration approaching 2g, as shown in Figure 5-1. This procedure is difficult for bushings with a fundamental as-installed frequency of about 6 Hz or if the system has high damping. In some situations the man-lift cannot be positioned close to the bushing. It is easy to excite perpendicular to the man-shake platform, but in the transverse direction exciting the bushing at arm's length may be difficult to generate large forces.

Note that for this bushing there was little searching for the resonant frequency of the bushing. The peak response is almost 2g. This might be a half or third of what it would experience in a 1g-qualification shake test. Note that there is a linear attenuation of the envelope at large amplitudes. When the response attenuates to about 1g, an exponential attenuation is observed. The linear attenuation is characteristic of friction-like damping and exponential attenuation is characteristic of viscous-like damping. To capture all three responses in one plot, the individual cycles cannot be distinguished. Figure 5-2 shows an expanded view of the sine sweep response.

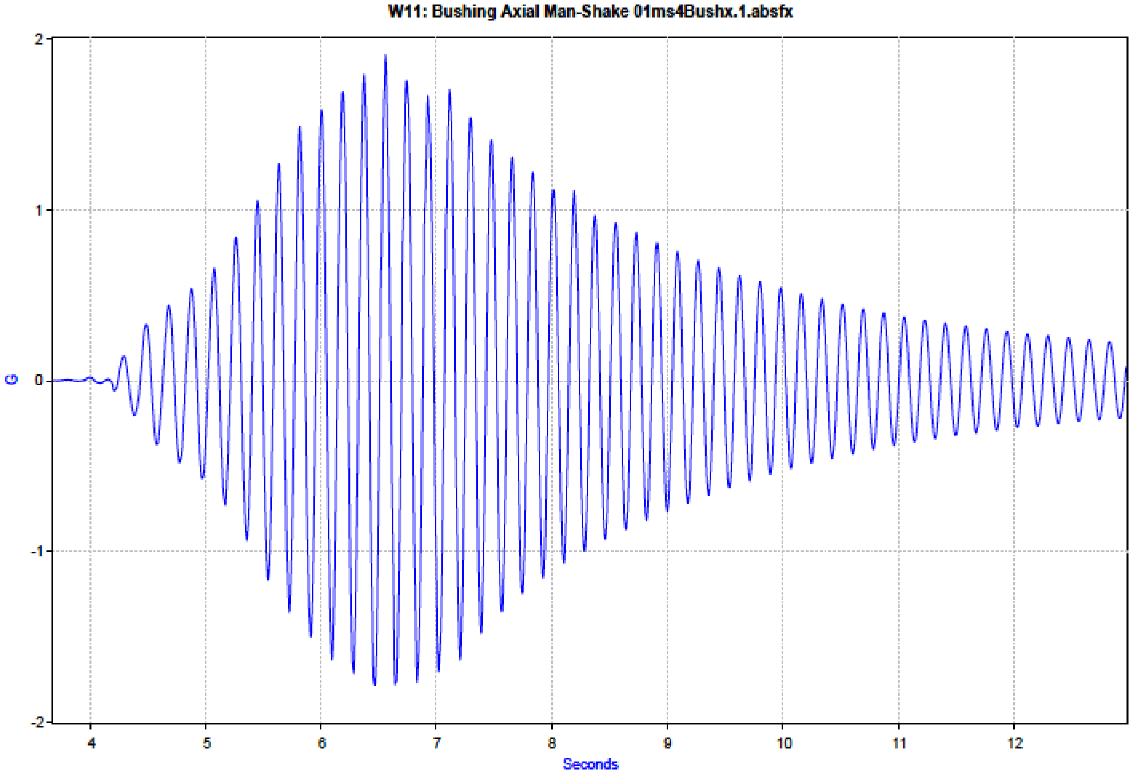


Figure 5-2
Expansion of the sine sweep response shown in Figure 5-1

Hand Impact Test

The hand impact test is done with the arm stiff and the top of the bushing is struck with the palm of the hand by rotating the upper body to strike the bushing. This tends to generate a longer duration impact with more low frequency energy content. Figure 5-3 shows an initial spike followed by an exponential attenuation. Closer examination below will show that the second bushing mode is excited.

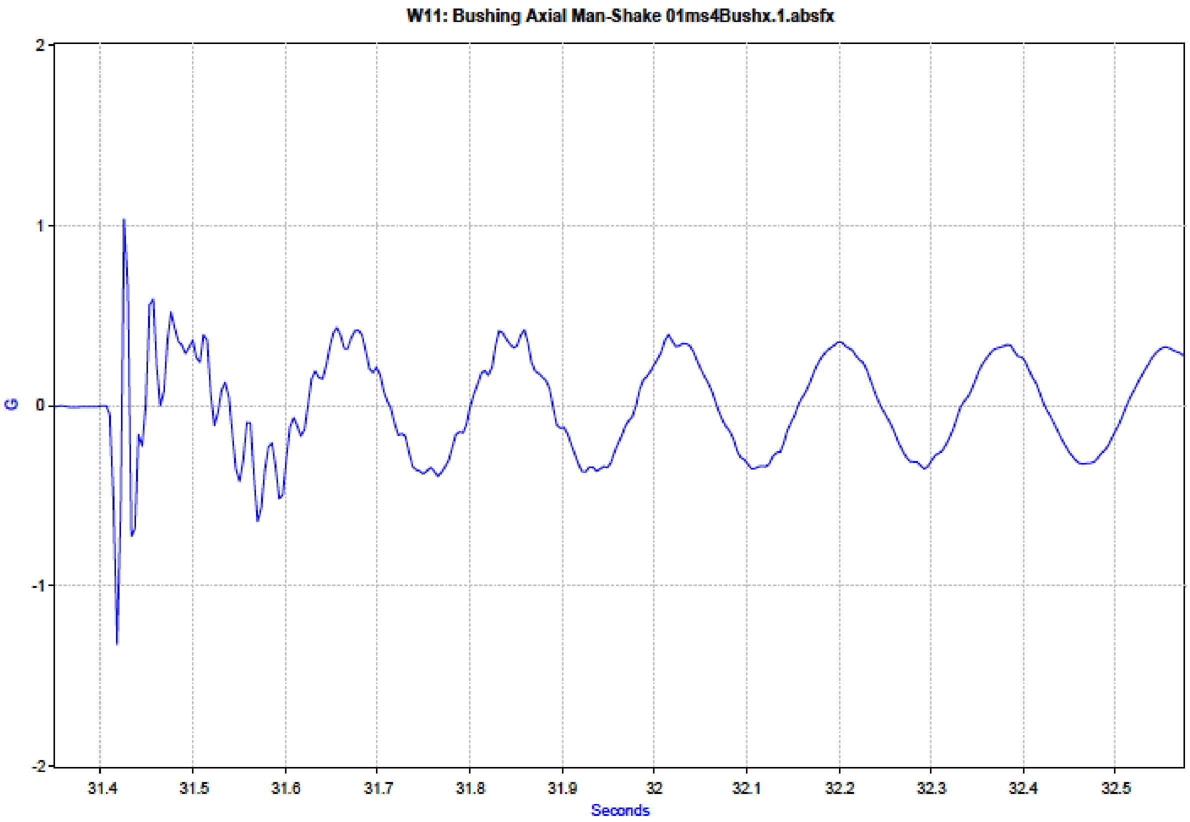


Figure 5-3
Expansion of the hand impact response

Rubber Mallet Impact

The third excitation is with a rubber mallet. A short, not necessarily hard blow, tends to also excite the second mode of the bushing.

Note that the entire sequence of three excitations takes only about 70 seconds to gather data for modes in one direction. There is a delay between excitations to allow the previous response to decay. In some cases, for very lightly damped systems, the attenuation can be stopped by hand to save time. The file size is only about 9000 samples per channel. Thus, when loaded into an Excel worksheet there will be 9000 rows and four columns (time, and acceleration values in the x, y and z directions). Data for responses from all three directions can be collected in one file, but this will generate long files that are not convenient to use in Excel. When using Excel, it is more convenient to collect the data for each direction in a separate file. That is, turn the accelerometer off and back on between each man-shake test sequence. If the man-lift does not need to be repositioned, the axial, transverse, and vertical test sequences can be done in less than five minutes. Generally, the vertical frequency is too high for a sine sweep excitation so a mallet blow is used. The accelerometer assembly is not repositioned between tests in the different directions, although it may be necessary to remove the accelerometer to turn it off and on (to start a new file) between each excitation in the man-shake test sequence.

Initially, the impact tests were done if it was not possible to do the sine sweep test. As will be seen below, the impact tests provide additional information on the second mode response of the bushing. The analysis that is suggested, which is discussed below, uses Excel. It will be useful to take a closer look at Figure 5-1 by expanding the response from each excitation. This can be done using Excel, but it is not as convenient. Generally, only data from the sine sweep response is needed to get the frequency and damping of the first mode.

Figure 5-2 shows an expanded view of the sine sweep part of the response so the individual cycles can be seen. Note that the sine sweep almost immediately becomes tuned to the natural frequency of the bushing. The amplitude of the response gradually increases over many cycles. After the release, the peak accelerations are not perfectly smooth on the positive excursions. The period of the motion is less than 0.2 seconds, so it is possible that the stop in the shaking was not instantaneous. The damping of this bushing was 1% of critical. The analysis of the data is discussed below.

Figure 5-3 shows an expansion of the hand impact. Initially there is a high frequency ringing that is close to the second mode of vibration of the stiff-mounted bushing. If this data was to be used to measure the fundamental frequency and damping, a longer segment of the ring down would be used and the "noisy" part with the second mode would be avoided.

Figure 5-4 shows an expansion of the mallet impact test. The response of the higher mode is relatively large compared to the fundamental frequency response. If this data was to be used to measure the fundamental frequency and damping, a longer segment of the ring down would be used and the "noisy" part with the second mode would be avoided.

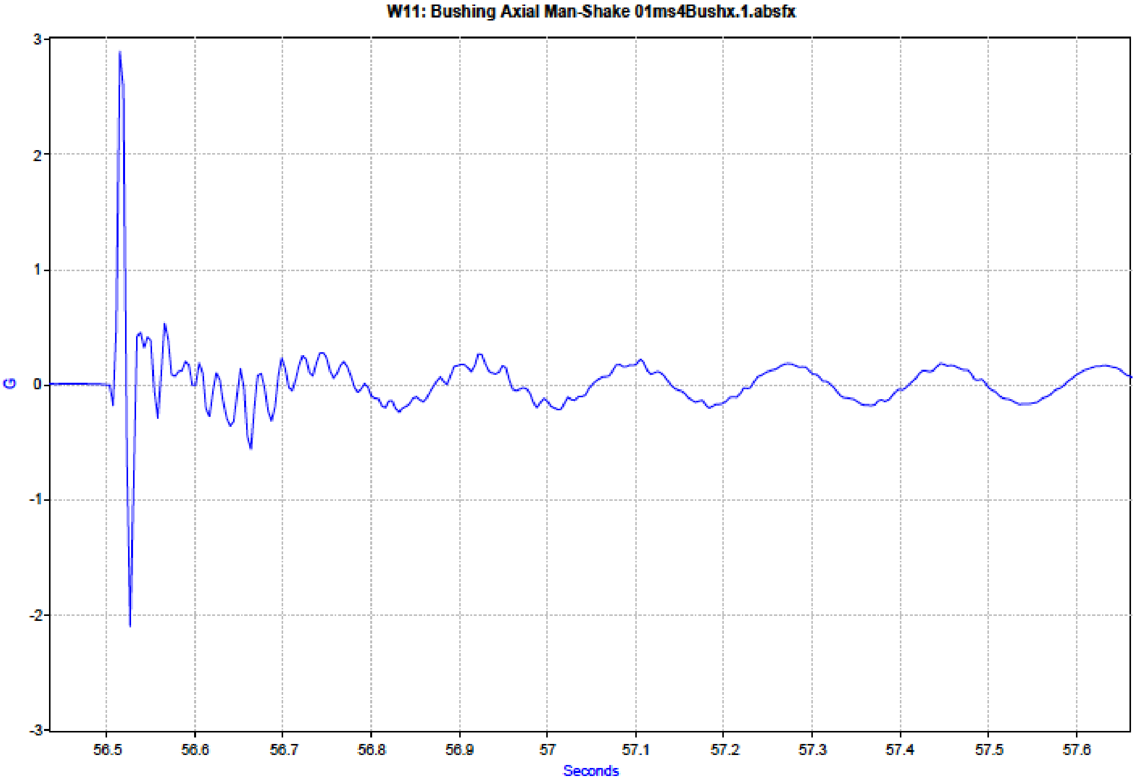


Figure 5-4
Expansion of the mallet response

6

TEST PROCEDURE

This procedure starts when it is assumed that the person doing the test is in the man lift adjacent to top of the bushing. The sine sweep test excitation is easier if the man lift is located so that the bushing can be pushed. Before installing the accelerometers, it is useful to get the feel of the excitation process by running through man-shake test sequence to see if a good response can be obtained in each direction. Getting a good response from the sine sweep test may take some practice.

Figure 6-1 shows a man-lift getting in position near the top of a composite 500 kV bushing at a site that is under construction. Conductors have not yet been installed on the transformer. The installation of a conductor significantly increases damping and can complicate the evaluation because the equipment at the other end of the conductor can also be excited and its response will also provide feedback into the measured response. When testing a bushing during the installation process, it is useful to measure the response before and after the conductor is added. Figure 6-2 shows the accelerometers installed on the bushing. Figure 6-3 show a sine sweep test on a different item of equipment.

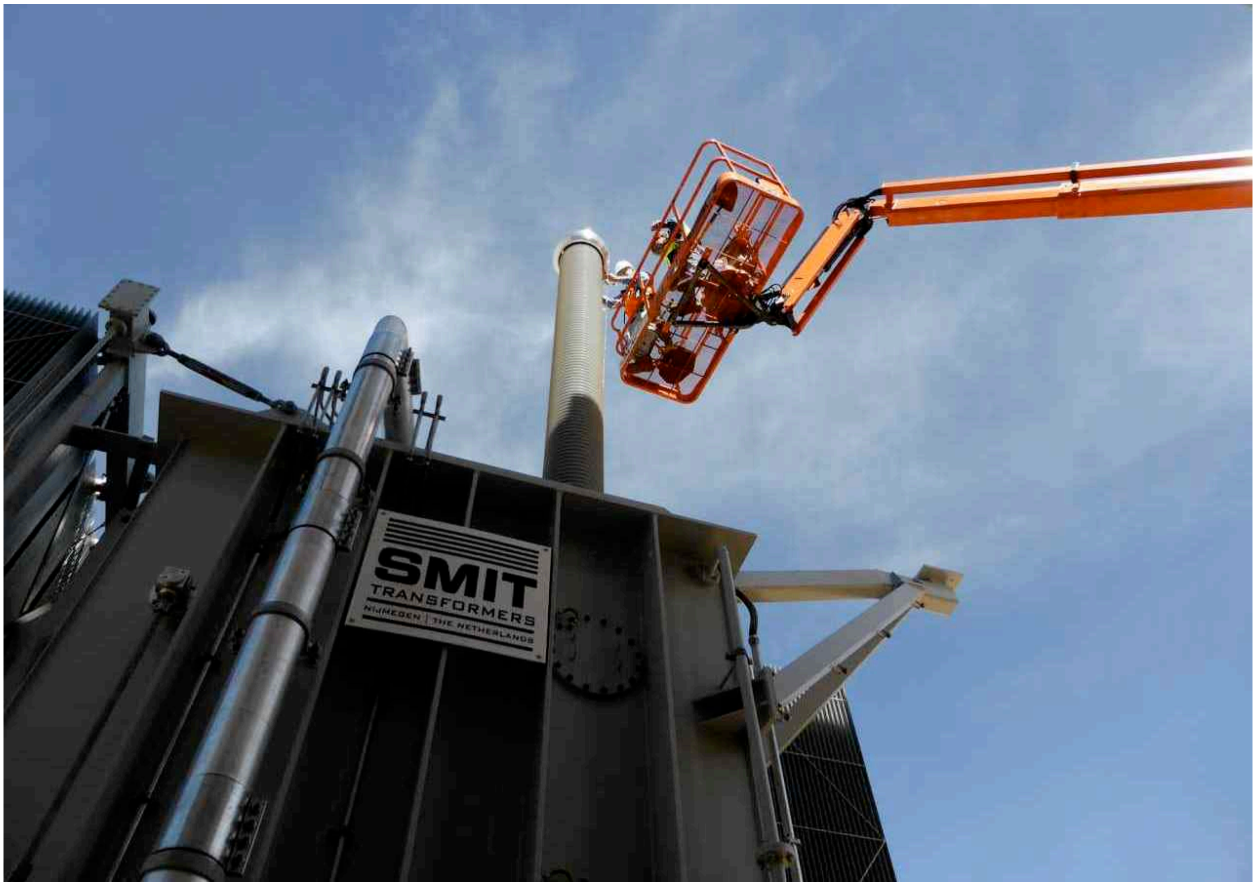


Figure 6-1
Man lift positioned at top of the bushing

Figure 6-2
Accelerometers attached to bushing terminal post

Figure 6-3
Sine sweep test on equipment

Because the individual collecting the data may be different from the person analyzing the data, it is important to carefully document each file. If a single bushing is being evaluated, all that is needed is the orientation of each man-shake test sequence. If one is evaluating a three-phase 230 kV transformer, tests should be run on each of the 230 kV bushings, the conservator, surge arresters, and several radiator assemblies. When access to a substation is available, several items of equipment may be evaluated from the ground without the need for an outage. In these cases documentation is more important and complex. In addition, time is typically limited, so the documentation process should be fast.

It is useful to standardize the orientation of the accelerometers, for example, always position the x-axis of the accelerometer along the longitudinal direction of the transformer tank. However, this may have to be adjusted when the mode of vibration is skewed to the “standard” orientation, as only a single fundamental mode is desired. Recall in Figure 3-2, the bushing modes of vibration were skewed to the principal axes, so excitation along a principal axis excites both horizontal modes and the data is difficult to analyze. It can be difficult to get the angle of excitation adjusted properly. The fastest way to document the orientation of the accelerometer is to take a picture, such as the example in Figure 6-2. A picture of an overview of the transformer can also be useful as it shows the orientation and the accelerometer number. Two accelerometers are typically used in tests for the reliability of redundancy, as the data is evaluated after leaving the site and a second shot at the test is usually not possible. In subsequent testing, where methods had been improved, I also marked a post-it with the equipment and file number and included it in the picture.

The on-off switch on the accelerometer is recessed. If a mechanical pencil with a sharp point is used to push the button, it is possible to miss the button so the accelerometer will not be turned on. The Phillips-head screwdriver provided with each accelerometer is a good tool for pushing the button. The unit has an internal light, which indicates if it is on, but in bright sunlight the light is difficult to see. Every time the unit is turned on and off, the file number is increased, so records can get out of sync. After several tests I will do a rough calibrations test (position the accelerometer in each of three orthogonal directions). This clearly marks a break in the collection of data and allows the file numbers to be resynchronized.

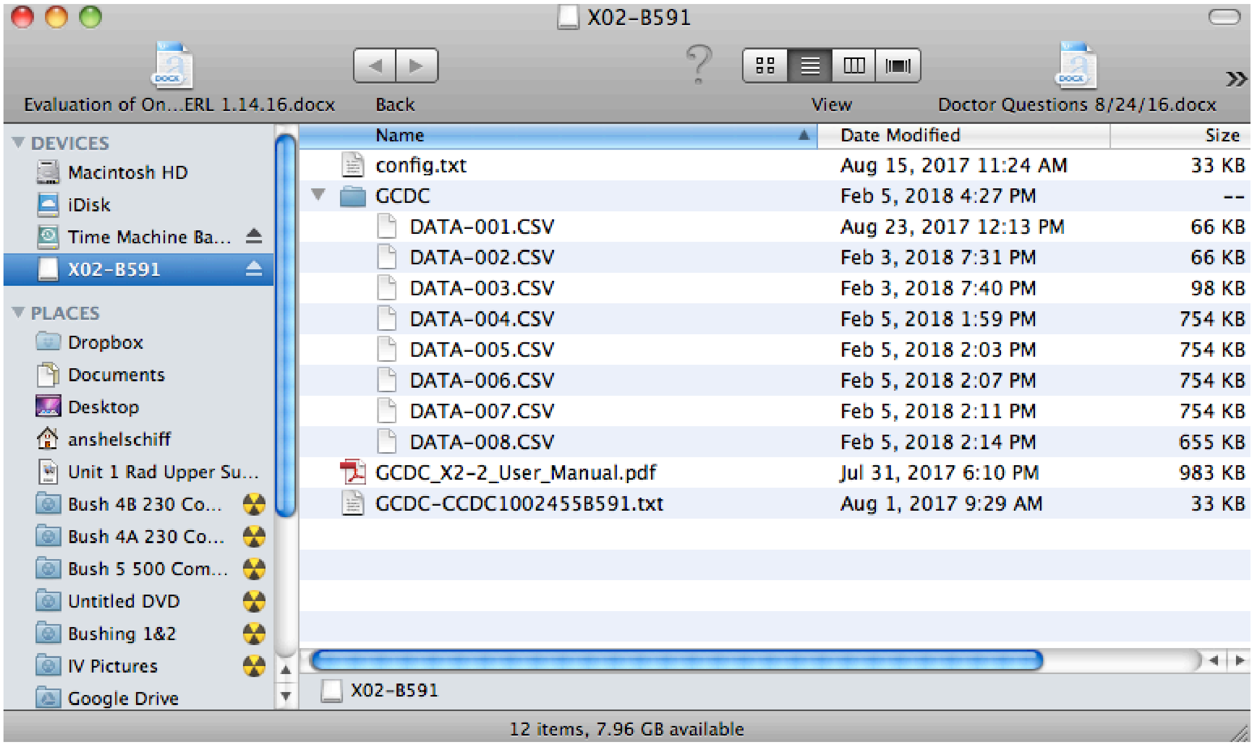
When doing tests in the field, where things can go wrong and the test cannot be rerun, it can be helpful to use two accelerometers for redundancy in case a unit is not turned on or has some other problem.

If a test generates more than 30,000 points on each accelerometer channel, the file will consist of two or more file segments, each 30,000 points, except the last segment, which may be shorter. When downloading the accelerometer, each file segment will have to be downloaded into its own Excel worksheet. The last line of each file has a designation indicating that it is the end of the file; that will not be present at the end of an intermediate file segment.

7

LOADING AND PREPARING DATA IN AN EXCEL WORKSHEET

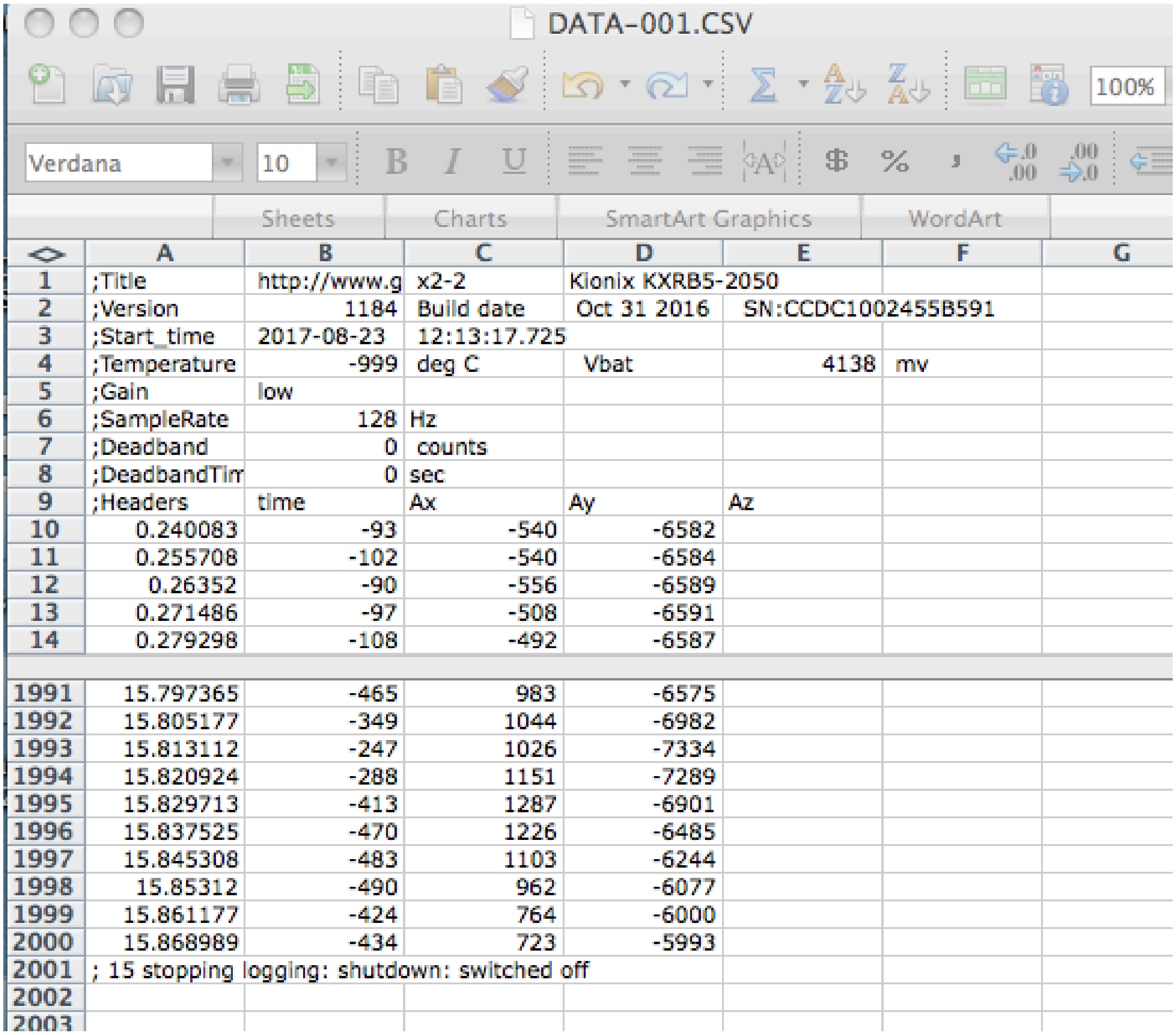
Remove the protective cap over the USB connector at the small end of the x-axis on the accelerometer assembly and plug it into a computer. An external disk drive will appear on the screen labeled with the end unit serial number. Open the drive and an image shown in Figure 7-1 will appear showing the contents of accelerometer assembly memory. In this picture the GCDC folder has been opened, which exposes eight file segments in .csv format. These files contain the data and can be opened in Excel.



Name	Date Modified	Size
config.txt	Aug 15, 2017 11:24 AM	33 KB
GCDC	Feb 5, 2018 4:27 PM	--
DATA-001.CSV	Aug 23, 2017 12:13 PM	66 KB
DATA-002.CSV	Feb 3, 2018 7:31 PM	66 KB
DATA-003.CSV	Feb 3, 2018 7:40 PM	98 KB
DATA-004.CSV	Feb 5, 2018 1:59 PM	754 KB
DATA-005.CSV	Feb 5, 2018 2:03 PM	754 KB
DATA-006.CSV	Feb 5, 2018 2:07 PM	754 KB
DATA-007.CSV	Feb 5, 2018 2:11 PM	754 KB
DATA-008.CSV	Feb 5, 2018 2:14 PM	655 KB
GCDC_X2-2_User_Manual.pdf	Jul 31, 2017 6:10 PM	983 KB
GCDC-CCDC1002455B591.txt	Aug 1, 2017 9:29 AM	33 KB

Figure 7-1
Content of accelerometer memory

Figure 7-2 shows the contents of the first data file, DATA-001.csv in an Excel worksheet. This is not the data from an actual bushing test.



	A	B	C	D	E	F	G
1	;Title	http://www.g	x2-2	Kionix KXRB5-2050			
2	;Version	1184	Build date	Oct 31 2016	SN:CCDC1002455B591		
3	;Start_time	2017-08-23	12:13:17.725				
4	;Temperature	-999	deg C	Vbat	4138	mv	
5	;Gain	low					
6	;SampleRate	128	Hz				
7	;Deadband	0	counts				
8	;DeadbandTim	0	sec				
9	;Headers	time	Ax	Ay	Az		
10	0.240083	-93	-540	-6582			
11	0.255708	-102	-540	-6584			
12	0.26352	-90	-556	-6589			
13	0.271486	-97	-508	-6591			
14	0.279298	-108	-492	-6587			
1991	15.797365	-465	983	-6575			
1992	15.805177	-349	1044	-6982			
1993	15.813112	-247	1026	-7334			
1994	15.820924	-288	1151	-7289			
1995	15.829713	-413	1287	-6901			
1996	15.837525	-470	1226	-6485			
1997	15.845308	-483	1103	-6244			
1998	15.85312	-490	962	-6077			
1999	15.861177	-424	764	-6000			
2000	15.868989	-434	723	-5993			
2001	; 15 stopping logging: shutdown: switched off						
2002							
2003							

Figure 7-2
Image of Excel worksheet showing data set DATA-001

The header associated with this vintage unit occupies the first 9 rows. The length of the header may change depending on when the unit is purchased, but for a given unit the format does not change. The contents are explained in the user manual, which is also contained in the memory. Note that line 6 shows the sample rate of 128 samples per second. I have split the screen so that the start and end of the file can be seen. The data is contained in four columns, time, and accelerations in the x, y, and z directions, respectively. The accelerations are shown in whole numbers. To convert the units to acceleration in g, divide each cell by 6554. The last line does not have data, but a comment indicating that the accelerometer was shut off. Had this not been the last segment of what has been defined as a file, this line would not appear.

The channel of interest is in the direction of the man-shake test sequence. Thus, if the first test sequence was in the x direction, this would be the axis of interest. Frequently it is necessary to remove the accelerometer assembly from the test item to turn it on and off. This will result in wild fluctuations of data at the start and end of the record. The accelerometer assembly may not have been installed perfectly level, so the data may have an offset. Had the bushing been installed at an angle, the accelerometer assembly should be installed aligned with the axis of the bushing, so some channels will have offsets. The channel aligned in the vertical directions will have about a 1g offset. The offset should be subtracted from the channel as well as any start and end noise before the data is plotted and analyzed. An initial plot may be needed to identify the presence of noise and offsets. You should get a plot that looks similar to Figure 5-1 if you recorded man-shake test sequences in each direction in separate files. The data should be inspected to see if it appears to be good and if there are anomalies.

The disk also contains the user manual, which identifies the number used to convert the accelerometer data into gs. The configuration file allows parameters to be configured, such as the sample rate and gain. The accelerometer has other features, which are not discussed here.

If you were able to generate a good sine sweep test, the first part of the record should be evaluated. If not, the hand or mallet impact parts of the test sequence should be evaluated. For evaluation, the data should be plotted in expanded form, as in Figure 5-2, so that individual cycles can be seen, which is required for the data analysis.

8

ESTIMATING THE FREQUENCY AND DAMPING

To measure the frequency, determine the duration of at least 5 cycles and preferably 10 cycles. One over this time interval (in seconds) multiplied by the number of cycles is the frequency in Hertz. The zero crossing at the start and end of the interval may not fall exactly on the data points that have been collected. By using more cycles, this small error is reduced.

To measure the damping, the logarithmic increment, δ, is determined. This calculation is based on the assumption that the system is a linear, viscously damped system. Recall that the data shown in Figure 5-1 indicates that the large amplitude response may have friction-like damping, but the error in the estimate will be small. The fraction of critical damping, zeta, is determined from the logarithmic decrement. The equation for determining the logarithmic decrement is given below. As the data in Figure 5-2 shows, the first few peaks may be distorted, so start with what appears to be clean data. Again, select at least 5 or 10 cycles (n) for the second peak, as this reduces the error if your data points do not exactly fall on the peak. There are other more complex methods of getting these estimates, and some provide additional information, but for the basic estimate of the frequency and damping this should give good results if the data is clean.

$\delta = 1/n (\ln (x_i/x_{i+n})$ For lightly damped systems

Where
x_i is the amplitude of the ith peak
x_{i+n} is the amplitude of the ith +nth peak

Zeta = $\delta / 2 \pi$

9

REVIEW OF DATA COLLECTION PROCESSES

For this review of the data collection and evaluation processes, it will be assumed that a single bushing will be evaluated. This process would be done for each bushing that is evaluated. Also, assume that the initial plan is to apply the man shake sequences along the following axes and in the following order: along the longitudinal axis of the transformer, along the transverse axis of the transformer, and along the vertical axis of the bushing, unless the modes of vibration are skewed.

It is assumed that the person collecting the data will be different from the person analyzing it. Ideally, pictures should be taken as described below and shown above. Since smart phones are very common, a separate camera may not be needed. It is suggested that a picture showing an overview of the item being tested be taken. If several items are to be test, pictures of the nameplates should be taken. If more that one subsystem on a given item (for example, A, B and C bushings on a transformer), it is suggested that a picture of the accelerometer installed on each bushing with a post it identifying the equipment, item (such as Bushing A at north end of transformer), the test (MS axial), and the file number. The same post it can be used for the three tests of Bushing A, where the direction of the new test and the new file number are added before a new picture is taken. Ideally, the picture of the bushing should include the background so that the accelerometer orientation can be identified from the picture.

Collect the Test Data

1 First install the hardware to attach the accelerometer to the bushing terminal. Before installing the accelerometer assembly, do a trial run of the man-shake test sequence in each direction. This process serves two purposes. First, it provides practice in applying the sine sweep test and will determine if the system frequency and damping are such that the sine sweep test can be done. For example, sine sweep cannot be done in the vertical direction because the frequency will be too high. Second, the horizontal modes of vibration may be skewed to the transformer longitudinal and transverse axes. This should usually be clear when exciting in the longitudinal direction the bushing will respond in the longitudinal and transverse directions. If this occurs, try to excite the bushing at an angle so that the response is only in the direction of excitation. This usually only occurs when the bushing is close to the corner of the tank cover. The accelerometers and the subsequent shaking should be aligned with the modes of vibration, so that only one mode is excited and the suggested analysis methods can be used. If the axes are skewed, this information has to be passed to the person doing the analysis, so that the report describing the results accurately reflects the situation.

2 Before installing the accelerometer on the transformer do a calibration test. That is, with the accelerometer turned on (check that the red light is blinking), hold the accelerometer level with the z-axis up for about 5 seconds, then rotate the unit four times about the x-axis with 90º turns, pausing about 5 seconds after each turn so when finished the unit is in its original orientation. Then rotate about the y-axis so the x-axis is pointing up and pause about 5 seconds. Now rotate 180º about the y-axis so the x-axis is pointing down. Finally, rotate the

unit about the y-axis 90º so that the accelerometer is in its original position and pause about 5 seconds, and then turn the accelerometer off. This process will give a rough calibration of the unit, depending on how accurately you position the accelerometer. It also provides an identifiable response separating tests. This would be the first file of the testing activity. If any files were collected before this test, the number of files should be noted so that the person analyzing the data knows which is the first file to evaluate.

Turn on the accelerometer and check that the red light is blinking. This may take a few seconds after the on button is pressed. Then replace the accelerometer on its support hardware and install the accelerometer assembly on the bushing using attachment hardware so that the accelerometer axes are aligned with the modes of vibration. For this review, it will be assumed that the accelerometer is installed with the x-axis aligned with the transformer longitudinal axis and the y-axis aligned with the transformer transverse axis.

3 Do the man-shake test sequence along the longitudinal axis of the transformer. Observe the ring down vibration after each excitation to see that it has largely attenuated. This may take about 20 seconds. If the item has very light damping, place a hand on the bushing to stop the motion after adequate data is collected, before applying the next excitation. The application of the three excitations (sine sweep, hand impact, mallet impact) should take about a minute. Note the file number.

4 Turn the accelerometer off. This sets the file length and it should be short enough so that the file only has one segment.

5 Turn on the accelerometer and repeat steps 3 and 4 exciting the bushing in the transverse mode with the man-shake test sequence.

6 Turn off the accelerometer. Note the file number.

7 Turn on the accelerometer and repeat steps 3 and 4 exiting the bushing in the vertical mode. This should only involve the impact excitations.

8 Turn off the accelerometer. Note the file number.

9 It is suggested that the accelerometer be removed from the bushing. Turn it on and do calibration run done. If multiple bushings or other tests are done, this will clearly separate data for each item.

The accelerometer should now have five new files, each with one file segment. The first and last files are calibration tests and the three center files are the tests along the x, y and z-axes. Repeat the process for each bushing and other items that are to be tested. Note the total number of files that have been recorded. If a false “on” bottom was pressed, there may be other short files. This can occur because the red light indicating that the unit is turned on is difficult to see in outdoor tests in direct sunlight. Occasionally a test needs to be repeated and should be documented.

Analysis of the Data

The data log and supporting documentation should be provided to the person analyzing the data. This should include a series of pictures as listed above and a written log identifying the specific equipment (bushings, radiators, etc.) and associated file numbers.

The following process should be applied to each bushing or other item that was tested. The following process describes the evaluation of a bushing man shake test sequence of a bushing.

10 After plugging the accelerometer into the computer and double clicking on the accelerometer's external drive icon, the memory content should look similar to that shown in Figure 7-1. Note that the drive contains the manual for the accelerometer and a Configtxt file that allows the user to set the accelerometer's gain, sample rate, size of the data file segments that it stores, and other control parameters. Double clicking on the GCDC folder should display a header describing accelerometer parameters and a list of all data file segments that have been collected. If the memory was empty before data collection started and no false starts were made, the number of file segments should match the information provided by the person who collected that data, as the length of each file should be less than the 30,000 data samples suggested in Section 4. Check the data log and determine the direction of the first test. For transformer bushings it is assumed that the x-axis is aligned with the longitudinal axis of the transformer tank. If only one bushing was tested, there should be 5 new data files. The first and last should be calibration tests.

11 Double click on the first data file collected and copy the contents, or at least the data, into an Excel worksheet. Column A identifies the time of each sample. First convert the data in Columns B, C and D into g values by dividing by 6554 for model x2-2 (for the unit described in this report; newer instruments may have different model numbers and correct information can be found in the manual). Open and plot the data in Columns A, B and C and confirm that the output corresponds to the calibration test performed before test data was collected. Column B is associated with the x-axis data. The data in each of the columns should be plotted. This should be a calibration run that lasts less than a minute and shows steps in the output as the accelerometer was rotated. The length and form of the record should indicate that it is calibration data and serves to check that the file count is in sync with the data log. Each plot of the data will have a characteristic form related to the sequence of rotations applied to the accelerometer in the calibration process.

12 The second file should be the data from the man shake test sequence applied along the longitudinal axis of the transformer. The three data columns (B, C and D) should be copied to an excel worksheet and each cell divided by 6554 to convert to g values. Then plot the data in Column B (the bushing response in the longitudinal direction or along the x-axis—the direction of the excitation). If a complete man-shake test sequence was done, a plot of the record should look like Figure 5-1, but it may have an offset (the accelerometer may not be perfectly level) and noise at the start and end when the accelerometer assembly was turned on and turned off and hand held. The offset should be removed. Because of the noise at the start and end of the record associated with the response, when the accelerometer is hand held, the mean value of the record cannot may not represent the offset. Select a portion of the record when the accelerometer is attached to the bushing and read the offset from the tabulated data. The offset should be removed and the data re-plotted. The sine sweep data is usually the best data for evaluation, as it has the largest amplitude. The start of the data may have one or more buildups and drops in the response, as the tester gets tuned to the resonant frequency. Eventually a large response should be achieved, which is then allowed to decay. Of the responses that are there (sine sweep, hand impact and mallet impact), select the one with the cleanest ring down. Find the start and end times for the selected response. The duration should be long enough to capture at least 10 complete cycles. The analyses may be

possible from the plot that contains all three plots, but it may be desirable to get an expanded view of the data. If this is the case, re-plot the data from the interval of interest, as illustrated Figure 9-1. Measure the time interval of the selected number of complete cycles. This time interval, divided into 1 and multiplied by the number of cycles, will be the frequency of the bushing. Using the procedure described in the second paragraph of Chapter 8, the damping can be estimated. Note that the sample points will not exactly fall on the zero crossing or peak response. By averaging over at least 10 cycles adequate accuracy can be obtained. If there is beating in the response, the longitudinal and transverse modes may be coupled or the vibration of the bushing may be skewed to the longitudinal direction. It is useful to look at the transverse response. An x-y plot of the two responses may identify the angle of the response. When testing, it can be difficult to align the direction of the excitation with the direction of the modes of the response, so that the frequencies and their orientation have to be done as part of the analysis process. Bushings in the corner of the cover may have mode shapes that are skewed to the longitudinal axis.

Go to the next file and repeat the process to get the estimates of the remaining modal frequencies and damping of the bushing.

13 Continue the process if other items were tested.

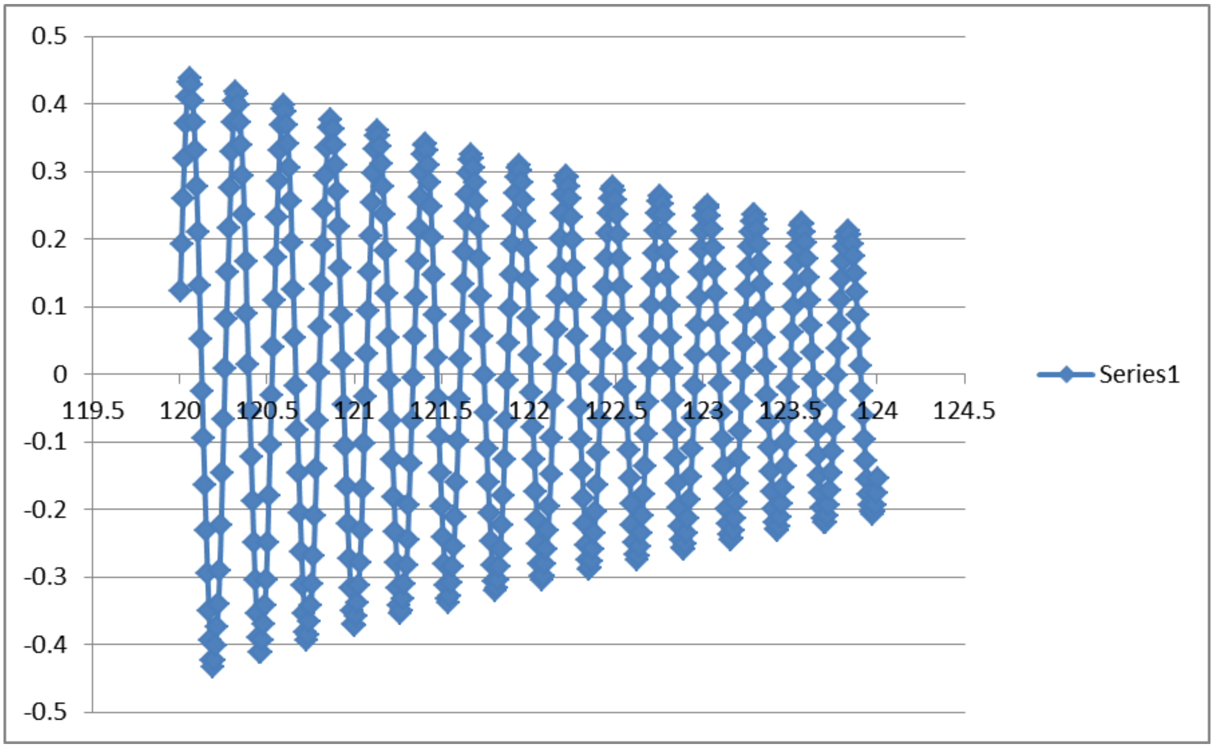


Figure 9-1
Excel plot of selected part of one of the responses

10

EXAMPLES OF DATA COLLECTION FOR OTHER SUBSTATION EQUIPMENT

The general form of most transformers is similar, so establishing a general test procedure is relatively easy and simplifies the testing and the analysis of the data. When evaluating other equipment in the substation, the regularity is wanting. The configurations of instrument transformers, disconnect switches, and shunt capacitors are quite different. In these situations more care is needed to document the test procedure so that when the data is evaluated it can be properly interpreted.

11

REFERENCES

Matt, H. and Filiatrault, A., “Seismic Qualification Requirements for Transformer Bushings,” University of California, Berkeley, Pacific Earthquake Engineering Research Center, Report No. SSRP-2003/12.

Institute of Electrical and Electronics Engineers, “IEEE Recommended Practice for Seismic Design of Substations,” IEEE Power Engineering Society, IEEE Std 693-2005.

A

HIGH REQUIRED RESPONSE SPECTRUM FOR STANDARD IEEE 693-2005 (IEEE STD 693-2005)

The High Required Response Spectrum for Standard IEEE 693-2005 (IEEE Std 693-2005) is shown in Figure A-1. In IEEE 693-2005, the high performance level test was to be performed with a shake table motion that met the requirements in Section A.1.2.2.1 and uses the spectrum described by Figure A-1 using a 2% damped RRS. Generally, equipment is qualified to the high seismic level of 0.5g RRS. To reach the target qualification level of 1g RRS, critical measurements are made so when critical response data was extrapolated to 1g, the results should meet the acceptance criteria of the standard. It is assumed that the equipment response is linear for the extrapolation. There are significant changes in the revised standard. In general, the high performance level shake-table test will be performed with a 1g 5% RRS rather than a 0.5g 2% RRS. This eliminates the need to extrapolate the response data. As before, bushings are to be tested as a stiff support structure. For bushings there are two other requirements. To account for the amplification introduced by the transformer, which supports the bushing, the peak amplification of the transformer at the bushing as-installed frequency is assumed to have a value of 2 or less. To meet this assumption, the excitation is doubled. In addition, to account for the fact that the as-installed frequency of the bushing will be reduced because of the flexibility of its support, the plateau of the RRS is extended to the stiff-mounted bushing frequency.

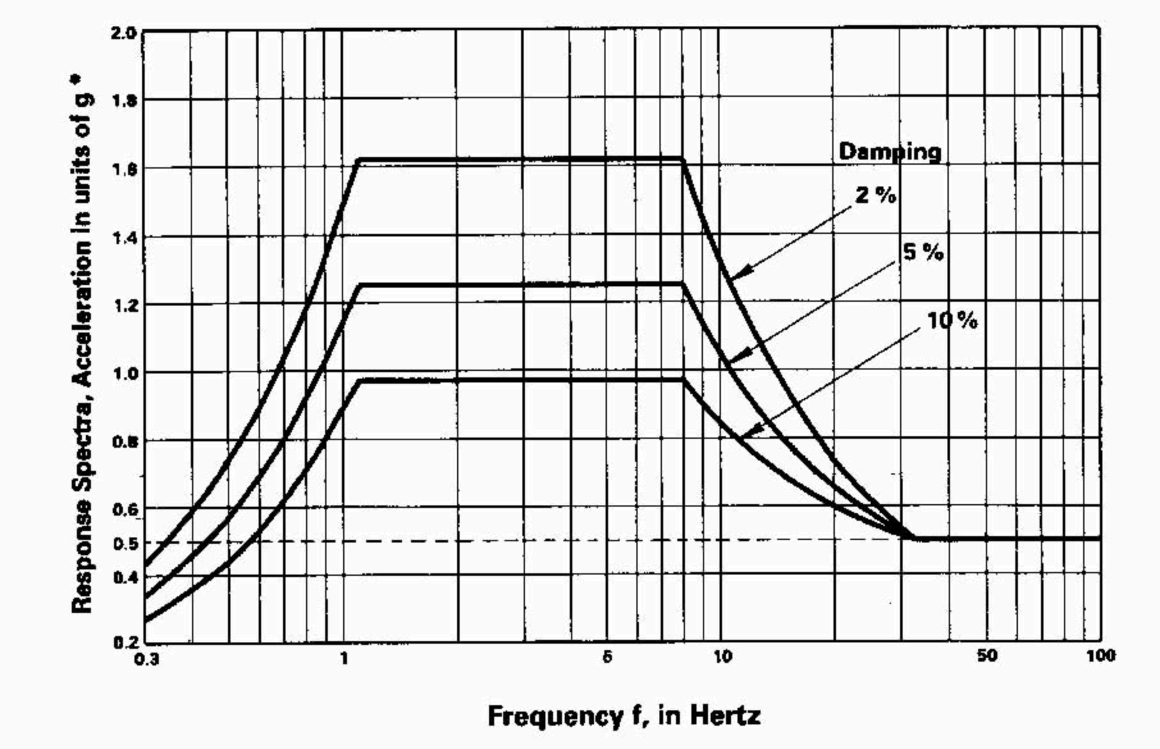


Figure A-1
High Required Response Spectrum, 0.5g from IEEE 693-2005

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