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Failure Analysis of Electrical Equipment under Operational Vibration

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Abstract

Equipment is subjected to vibration due to operating environment, transportation, handling and earthquake. Vibration results in dynamic loading, wherein failure of equipment depends on magnitude and frequency content of vibration. Equipment should perform its desired function during and/or after the vibration. The need to understand the effects of vibration and shock on equipment reliability is paramount. Vibration qualification is performed to determine if a product can withstand the rigors of its intended use environment, to ensure the final design will not fall apart during shipping, for environmental stress screening to weed out production defects, or even as a form of accelerated stress testing. Vibration tests are commonly used to improve the reliability of instruments, sub components and equipment or a system. Earthquake is the natural disaster which results in three-dimensional ground vibrations. Failure analysis of electrical equipment subjected to operational vibration environment is presented in this paper.

Keywords: Damping, Resonance Frequency, Vibration

1. Introduction

Vibration is mechanical oscillation about a reference position. Vibration can be generated by various everyday processes and experienced in our homes, during transport and at work or can be a rare phenomenon like an earthquake. Vibration in mechanical systems is a destructive and annoying side effect of a process, but is sometimes generated intentionally to perform a task.

Vibration is described by three factors: amplitude, or size; frequency, or rate of oscillation; and the phase or timing of the oscillations relative to some fixed time. Every system, even an apparently rigid one, has a certain degree of elasticity, and is therefore deformable. The system can be outlined as a mass, rigidity, represented by a spring and damper. Frequency at which a system oscillates after initial excitation is the natural frequency of the system and it is specific for each system.

Greater the mass and lesser the rigidity, lower will be the natural frequency. Oscillation amplitude diminishes in time until the system stops oscillating due to damping effect. Resonance occurs when the external forcing frequency coincides with the natural frequency of the system. At resonance, the amplitude of oscillation tends to increase indefinitely, and the structure is subjected to increasing deformation, which may cause failure. Vibration is undesirable in most of the cases, resulting in loss of energy and creating of unwanted noise.

Vibration is a major cause of machine and plant downtime, as well as a safety concern. Design and testing of equipment/components for vibration dynamic loads can prevent premature failure; ensure quality and reliability of product. This in turn results in safe working environment. Earthquake Engineering and Vibration Research Centre capable of performing a diverse range

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of vibration and seismic qualification requirements on equipment, sub-assemblies and components as per National and International standards has been established at CPRI, Bengaluru. Vibration qualification of failure analysis of electrical equipment to operational vibration environment is presented in this paper.

2. Vibration Environment

Equipment / products will experience vibration under following stages in the lifecycle:

- Manufacture/Assembly: Whilst the equipment is being manufactured, components are often subject to shock and vibration. Sometimes they may be dropped while handling.
- Transportation: Equipment are subjected to vibration during transportation. Proper design of packaging can avoid failure of equipment during transportation[1].
- Installation: Equipment that must be installed needs to withstand manual handling.
- Service environment: The environment in which the equipment must operate. Environmental condition vibration may be due to the equipment itself or vibration transferred from the surrounding environment. Equipment with moving parts generally generates vibration, equipment is expected to function normally under vibration and shock due to environmental conditions.
- Earthquake: Equipment are subjected to simultaneous three-dimensional vibration during earthquake[2].

Understanding the source and level of vibration is the primary requirement for design of any equipment/components.

Based on the level of vibration and their frequency content, measures should be taken to design and qualify the equipment. This will ensure quality of product. Careful design usually minimizes unwanted vibrations generated by equipment during its regular process. In addition to careful design, proper installation of rotating machines and maintenance can minimize the unwanted vibration. Proper packing can protect equipment from transportation vibration. However, vibration due to earthquake is inevitable, only its effects on the equipment can be reduced by proper design. Earthquake ground motion are typically broadband random in nature with higher energy in the lower frequency range (less than 10Hz), while vibration due to service environmental condition and transportation are generally high frequency in nature.

3. Vibration Qualification

Vibration qualification of equipment can be carried out by actual testing and finite element analysis. Usually, analysis is carried out at the initial design stage and is validated by actual testing. Precise modelling of complex electrical equipment for analysis is difficult, also functionality of equipment cannot be evaluated by analysis, hence most of electrical standard recommend qualification by actual testing. Vibration testing is carried out by simulating vibration using electrodynamic vibration system and servo hydraulic vibration system. Equipment / component to be tested is bolted to the vibration system with suitable fixture and subjected to required level of vibration. Maintaining structural integrity and functionality are the fundamental acceptance criteria.

IEC 60068-2-6[3] vibration-sinusoidal, IEC 60068-2-64[4], vibration-broadband random are the generic standards for vibration testing. These standards cover testing procedure and evaluation criteria. Testing shall be carried out as per product specific standards, if product specific standards are not available then; vibration testing is conducted as per generic standards by selecting suitable vibration parameters based on application of equipment.

Structural integrity of the equipment/components after vibration test is verified by conducting resonance search test before and after vibration test and comparing the natural frequency. Drastic change in natural frequency after vibration test indicates the equipment under test is not structurally integral. Resonance search test is conducted by base excitation. Test specimen is excited with sinusoidal sweep vibration of constant acceleration over the frequency range of interest. Response acceleration at critical locations on test specimen and excitation acceleration are recorded. Transfer function of response to excitation acceleration in frequency domain (Bode plot)[5] is computed using the data.

Functioning of equipment before, during and after vibration test is evaluated. Specific functional requirements of each equipment are based on qualifying standard. For example, in case of energy meter accuracy of energy meter before and after vibration test is measured, deviation in accuracy after vibration test shall be within limit as specified in the relevant standard. Malfunctioning of equipment during vibration test are also checked, to know the functional capability of equipment under vibration environment.

3.1 Mounting

During vibration testing equipment/component should be fastened to the vibration test system directly or by means of suitable fixture by its normal means of attachment in service, such that the gravitational force acts on it in the same relative direction as it would in normal use. Fixtures used to simulate actual mounting condition should be rigid and should not have resonance frequency in the frequency band of interest. Fixture resonance will amplify the input vibration excitation and may result in failure of test specimen.

3.2 Vibration Levels

Vibration qualification level can be obtained from relevant standard or based on actual field vibration[6] data measured at the mounting location.

In order to assure the quality of equipment, equipment has to withstand tests of reasonable duration that simulate the service conditions seen throughout its expected life. Simulated long-life testing (endurance testing) can be achieved by following ways:

a) Amplification: Amplitude of vibration is increased and the time base decreased
b) Time compression: Amplitude is retained and the time base is decreased by increase of frequency
c) Decimation: Time slices of the historical data are removed when the amplitudes are below a specified threshold value.

Amplification method is generally used.

4. Failure Analysis

Vibration qualification is specifically aimed at demonstrating the ability of the equipment to withstand the type of environmental vibration normally expected in field conditions. Operational environmental vibration can be simulated by sinusoidal vibration or random vibration. Random vibration method is more realistic, vibration experienced by the equipment in field is random in nature.

Common failures noticed during operation vibration are,

1. Change in structural integrity,
2. Functional failure and
3. Visual deformation/dislocation.

4.1 Change in Structural Integrity

Panel is mounted close to rotating machines in actual field conditions. Vibration generated from heavy rotating machines is transferred to the panel. Panel is expected to function under these vibrating conditions. In addition to functioning, it shall maintain its structural integrity.

Panel was mounted on vibration table simulating actual field mounting condition. Photograph of Panel mounted on shake table is shown in Figure 1.

Panel was subjected to random vibration from 3 to 250 Hz with 11.28 m/s^2 rms value for 2 hours 30 minutes in each axis[4]. Random vibration test profile is shown in Figure 2. Performance tests of panel were carried out before and after test. During vibration qualification, Panel was in energized condition, output connected to a test motor and functioning aspects monitored. Panel was meeting functional requirements during and after vibration test.

Resonance frequencies of panel were evaluated before and after operational vibration simulation to assess the structural integrity. Resonance was found by sinusoidal sweep vibration with constant low-level acceleration of 2 m/s^2 for 2 to 200 Hz frequency range[3]. Resonance frequency found before and after vibration test is shown in Table 1.

Change in resonance frequency and corresponding deduction in stiffness as per IEC 60068-3-8[7] guidelines is shown in Table 2. Acceptable limit is based on application; generally, change in resonance frequency of less than 20% is acceptable for electrical equipment[8].

Change in resonance frequency due to operational vibration simulation in front to back direction is 6.56% and in side-to-side direction is 13.64%. Hence, it can be concluded that Panel is structurally integral and capable of withstanding operational vibration in horizontal direction.

However, change in resonance frequency due to vibration in vertical direction is 73.50% at the top of cubical and 36.75% at centre of gravity of panel. Results

Table 1. Resonance frequencies

Direction	Location	Resonance frequency, Hz	
		Before vibration test	After vibration test
Front to back	Top of panel	3.81	3.56
	Centre of gravity	3.81	3.56
Side to side	Top of panel	5.50	4.75
	Centre of gravity	5.50	4.75
Vertical	Top of panel	50.00	13.25
	Centre of gravity	21.25 & 50.00	13.44

Horizontal Direction

Vertical Direction

Figure 1. Panel mounted on shaketable.

Table 2. Reduction in stiffness

Resonance frequency decrease, %age	Reduction in stiffness, % age
2	4
5	10
10	19
20	36

indicate drastic reduction in structural integrity/stiffness of panel (Table 2).

Typical resonance plots before and after vibration qualification in vertical axis is shown in Figures 3 and 4.

After test in vertical direction, panel was subjected to visual inspection. It was observed that door hinges and drive mounting plate brackets were sheared. Change in resonance frequencies even without visible damage in a test sample also indicates loss of structural integrity.

4.2 Functional Failure

Equipment not performing its intended function during and/or after operational vibration is functional failure. In addition to this auxiliary circuit and normally open/normally closed contact shall not malfunction to avoid false signal/alarm.

Functional failure can be due to:

1. Components failure
2. Components dislocation

4.2.1 Components Failure

Components in the equipment shall be designed to withstand the operational vibrations. Designs are

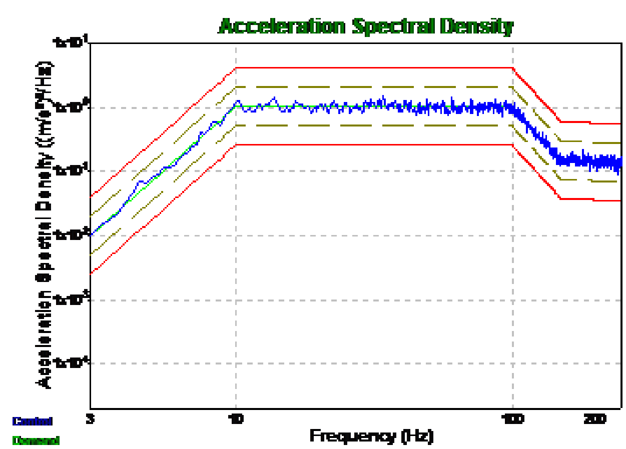
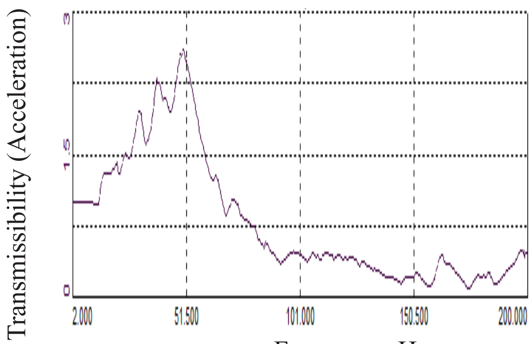
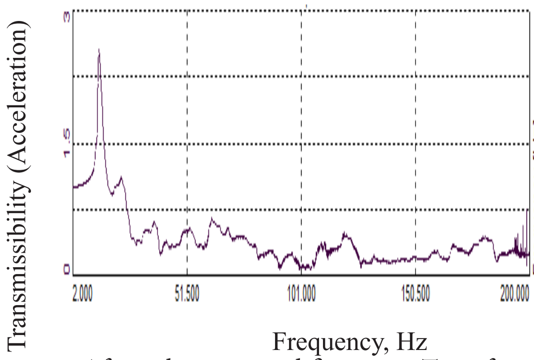


Figure 2. Random vibration plot.

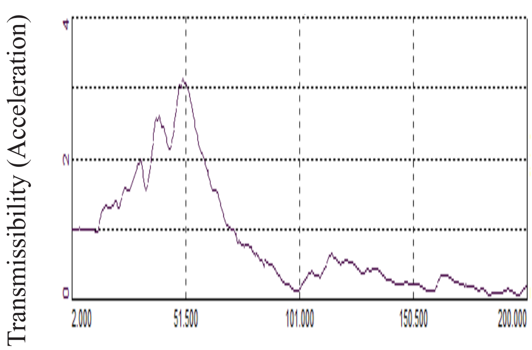


Frequency, Hz
Before vibration qualification – Top of panel

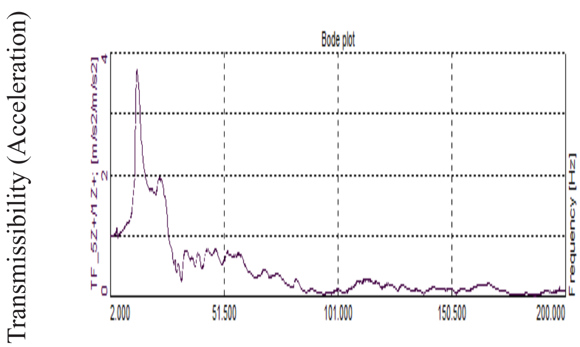


Frequency, Hz
After vibration qualification – Top of panel

Figure 3. Resonance plot.



Frequency, Hz
Before vibration qualification – Centre of gravity



Frequency, Hz
After vibration qualification – Centre of gravity

Figure 4. Resonance plot.

Figure 5. Relay mounted on vibration table

validated by actual testing at component level. Vibration amplification due to particular location of component inside the equipment and its mounting configuration shall also be considered while designing/selecting components. Heavy components like transformer, inductor is usually mounted at the base of equipment. Component failures are usually noticed in low voltage moving contact type relays. Solid state electronic components performance is comparatively good when subjected to operational vibration.

Figure 5 shows relay mounted on electrodynamics shaker system. Relay was subjected to vibration response test and functional checks were carried out during vibration.

During vibration response test, relays are kept in energized condition and operating value is set at highest sensitivity[9]. Output circuit, Normally Open (NO) and Normally Closed (NC) contacts were monitored for change in status. Change in status of contact observed during vibration is shown in Figure 6. Status of contact is changing continuously accounts to failure of equipment and may lead to malfunction of the entire system. Component failure is mainly due to localised resonance frequencies, improper component mounting and bad workmanship.

4.2.2 Components Dislocation

Mounting configuration of each component are designed by considering resonance of complete equipment, local resonance due to component mounting configuration and mass distribution. Additional supports/fasteners for heavy components and components with cantilever action can reduce chances of dislocation.

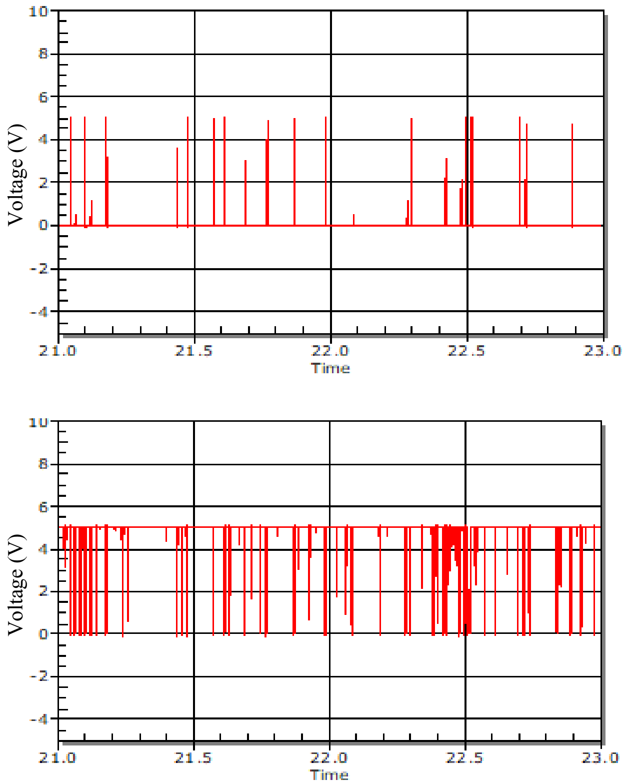


Figure 6. Change in status of relay contact.

Photograph of electronic modules dislocated during operational vibration is shown in Figure 7. In this case electronic modules were in functional state, but failure is due to component dislocation. Proper mounting arrangement with additional support to avoid cantilever action can solve these issues.

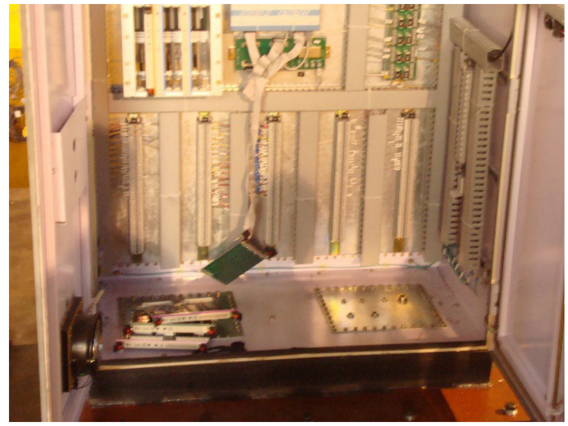


Figure 7. Dislocated electronic modules.

Figure 8. Panel door dislocated.

4.3 Visual Deformation/Dislocation

In some cases, equipment maintains their structurally integrity, but visual deformation/dislocation of part of enclosure or components occurs due to fatigue or improper design. These types of failures usually do not affect functional aspects of the equipment and main structure is also intact. Photograph of Panel door dislocated during operational vibration evaluation process is shown in Figure 8.

Acceptance of these failure without affecting structural integrity and functional aspects depends on application of equipment or field conditions.

5. Conclusions

Nature of electrical/electronic equipment failure due to operational vibration environment is presented in the paper and contributing factors to failure are discussed.

Possible failures that are; change in mechanical integrity, functional failure and visual deformation and dislocation are discussed with case studies. The levels of vibration, frequency content, design miscalculations, localised resonance frequencies and faulty mounting conditions are some of contributing factors. It's important for an equipment to maintain its mechanical integrity before and after vibration test. Both mechanical and functional attributes shall be checked for each equipment based on standard specifications or applications.

In case the equipment maintains its mechanical integrity, minor damage and dislocation is acceptable if the relevant specification permits. However, it has to be ensured that component failure should not lead to failure of the entire system. In case of equipment used in critical facilities like defence telecommunications, nuclear power plant and hospitals any mechanical or functional failure are not acceptable.

Designing of equipment, component and mounting configuration considering failure patterns can prevent future failures and ensure reliability of equipment. Assessing operational vibration environment in terms of amplitude, frequency and determination of dynamics properties of equipment plays vital role in design.

Power utilities may utilize the state-of-the-art facilities available at CPRI to ensure reliability and safety of electrical equipment.

6. Acknowledgement

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