13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3252

QUALITATIVE ASSESSMENT OF SEISMIC RESPONSE OF INTERNAL COMPONENTS OF POWER TRANSFORMERS

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SUMMARY

This paper discusses internal packaging of transformers and will identify possible dynamic response characteristics and modes of failure important to their seismic performance. Optimal electrical performance requires boltless design of core, which consists of sheets of steel laminations. This requires a high degree of design sophistication to ensure that adequate structural strength and rigidity are provided. Fault and gravity forces have so far determined the design stresses. The objective of this ongoing study is to determine if seismic forces can have adverse effect on internal packaging that can impact long term performance of transformers. A challenge to quantifying this is that inspection of internal components after an earthquake is not conducted. However, there has been reportedly unexpected loss of many transformers in the years following past earthquakes that can be attributed to sustained internal damage during these events and loss of longevity. The objective of this ongoing analytical study is to determine the impact of seismic forces on internal components of typical transformer and to qualitatively assess its impact on transformer electrical performance. This will also allow better determination of economic justification of base-isolation, as discusses in a companion paper, as a rehab strategy.

INTRODUCTION

Motivation

Substations are critical components in a power system. Performance of substations during past earthquakes has not been satisfactory and many key components such as transformers and bushings have sustained significant damage. An important issue to consider in seismic design and in development of rehabilitation strategies for critical substation equipment is the impact of an event on their long-term reliability and longevity. Shaking of internal components of power transformers can very likely have an adverse impact on its long-term performance and its reliability. For example, LADWP Sylmar station has reportedly lost many transformers unexpectedly in the years following the 1971 San Fernando earthquake.

The internal components of transformers are mechanically designed to withstand substantial forces caused by fault currents. These forces include radial forces applied to the inner and outer windings and axial forces applied to the windings. Hence, the internal components are expected to show a good behavior in resisting earthquake excitations and transferring the inertia loads to their core and avoiding structural

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damage. However, the ability of transformers to function depends on keeping the insulation of different parts of the system with substantial difference in electric potential intact. Any damage to the insulation system or anything that causes different components to get closer than their design values produces the possibility of electrical discharge that results in malfunctioning of the transformer with immediate or long-term implications. Furthermore, manufacturing of transformers requires lowering of the core-coil system into the tank from the top without any mechanical connection at the base, often with large gaps between the core-coil assembly and the tank. During transportation wood blocks are inserted in these gaps to prevent sliding and rocking, however, these are removed afterward. This raises the possibility of flexural and rocking of the core-coil assembly that can jeopardize electrical performance. Furthermore, based on study of the structure and design of internal components, site visits to inspect opened transformers, and discussions with technical staff at utility companies along with limited information from past performance under earthquakes, additional probable failure or damage modes are identified. In the following sections first a description of internal packaging is provided. This is followed by discussion of possible modes of failure that are being studied using simplified analytical models.

DESCRIPTION OF THE INTERNAL COMPONENTS

Core Structure

The core is made of thin layers or laminations of dielectric steel especially developed for its good magnetic properties. The magnetic properties are best in the rolling direction. Therefore, in a good core design this should be the direction of the electrical flux. The lamination can be wrapped around the cores or stacked. Wrapped or wound cores have few, if any, joints so they have the ability to carry the flux nearly uninterrupted by gaps. However, the stacked cores have gaps at the corners where the core steel changes direction. These results in poorer magnetic characteristics compared to wound cores. Stacked cores are much more common in larger power transformers (Fig. 1a). This figure shows three laminated limbs (vertical elements) and the lower yoke (horizontal element). The top yoke is placed after the coils are lowered into the limbs. The laminations for both types of cores are coated with an insulating coating to prevent development of large eddy current paths, which could lead to high losses.

In stacked cores of core-form transformers the coils are circular cylinders that surround the core. Hence the preferred core cross section shape is circle since this will maximize the flux carrying area. In practice, the core is built in steps that approximate a circular cross section (Fig. 1b). The space between the core and the innermost coil is needed to provide insulation clearance for the voltage difference between the winding and the core, which is at ground potential and is also used as structural elements. (Del Vecchio [1])

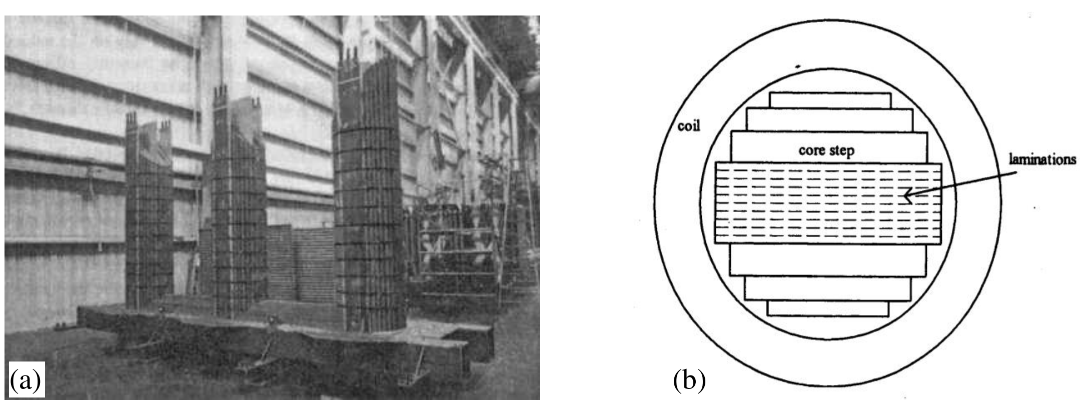
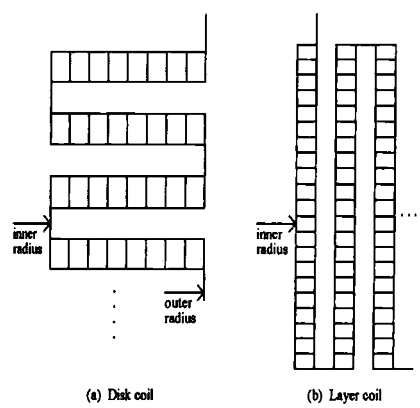


Figure 1. (a) Three-phase stepped core for a core-form transformer without the top yoke (Heathcote [2]) (b) Limb cross-section of a 7-step taped core. (Del Vecchio [1]).

Windings
There are two main methods of winding the coils for core-form power transformers. Both are cylindrical coils, having an overall rectangular cross section. In a disk coil, the turns are arranged in horizontal layers called disks, which are wound alternately out-in, in-out (Fig. 2a). The winding is usually continuous and the last inner or outer turn gradually transitions between the adjacent layers. The turns within a disk are usually touching and a double layer of insulation separates the metallic conductors. There is open space between the disks except for structural separators called key spacers. This allows room for cooling fluid to flow between the disks, in addition to providing clearance for bearing the voltage difference between them (Del Vecchio [1]). Loss of these key spacers due to a combination of prestressing loss and earthquake loading is one possible mode of damage.

In a layer coil, the coils are wound in vertical layers, top-bottom, bottom-top, etc (Fig. 2b). The turns are typically wound in contact with each other in layers that are separated by means of spacers so that cooling fluid can flow between them. These coils are also usually continuous with the last bottom or top turn transitioning between the layers.



a) Disk coil b) Layer coil

Figure 2. Two major types of coil construction for core-form power transformers (Heathcote [2]).

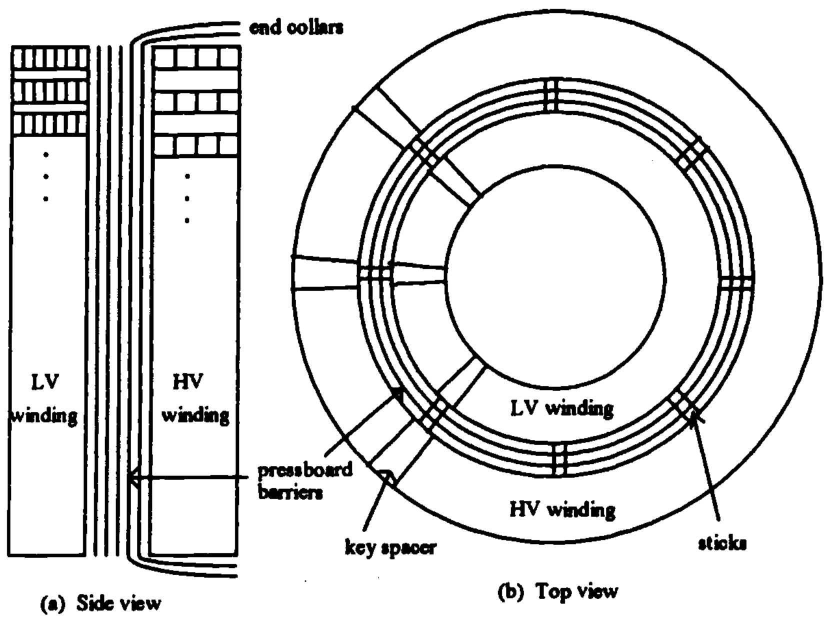
Both types of windings are used in practice and one or the other can be more efficient in certain applications. Generally, they can both be designed to function well in terms of ease of cooling, ability to withstand high voltage surges, and mechanical strength under short-circuit conditions.

Transformer Cooling
Electric resistance, changing flux in the electrical steel, and stray time-varying flux in metallic tank walls and other metallic structures result in losses inside a transformer. These losses lead to temperature rises that must be controlled by cooling. The primary cooling media for transformers are oil and air. In oil cooled transformers, the coils and core are immersed in an oil-filled tank. Radiators or other types of heat exchangers are usually used to circulate the oil so that the ultimate cooling medium is the surrounding air or possibly water for some types of heat exchangers. During past earthquakes damage to transformers has happened due to radiator and other peripheral equipment connection failure.

The cooling medium in contact with coils and core must provide adequate dielectric strength to prevent electrical breakdown or discharge between components at different electric potentials. Oil immersion is more common in higher voltage transformers because of its higher breakdown strength compared to air.

Insulating Structure

Transformer windings and leads operate at high voltages relative to the core, tank, and structural elements. Also, different windings and even different parts of the same winding have different voltages. This requires providing some form of insulation between these various parts to prevent voltage breakdown or corona discharges. The surrounding oil or air that provides cooling has some insulating value. The type of oil most commonly used is called transformer oil. Further insulation is provided by paper covering over the wire or cables. This paper has a high insulation value when saturated with oil. Other types of wire covering are sometimes used for specialty applications. Pressboard is another insulation structure that is generally available in sheet form, often made in cylindrical shape. This is a material of cellulose fibers compacted together into a fairly dense and rigid matrix. Key spacers, blocking material, pressure rings, and lead support structures are also commonly made of pressboard (Fig. 3).



a) Side section b) Top view

Figure 3. Major insulation structures consisting of multiple barriers between windings (not all key spacers or sticks are shown Del Vecchio [1]).

Although normal operating voltages are quite high, 10-500 kV, the transformer must be designed to withstand even higher voltages that can occur if lightning strikes the electrical system or when power is suddenly switched on or off in some part of the system. However infrequently these happen, unless the insulation is designed to withstand them they could permanently damage the insulation, disabling the unit. These events usually have short durations. There is a time dependency on how insulation breaks down. A combination of oil and pressboard barriers can bear higher voltages for shorter periods of time. Therefore, a high-voltage short-duration impulse is no more likely to cause breakdown than a long-duration low-voltage pulse. This means that the same insulation that is used to withstand normal operating voltages that are continuously present can also withstand the high voltages briefly present when lightning strikes or during switching operation. Lightning or surge arrestors are used to limit these abnormal voltages to insure that they do not exceed the breakdown limits determined by their expected duration. These arrestors thus guarantee that the voltages will not go above a certain value so that breakdown will not occur, provided their durations remain within the expected range.

Due to the different dielectric constants of oil or air and paper, the electric stresses are unequally divided between them. Because the oil dielectric constant is half of that of paper and that of air is even a smaller fraction of that of paper the electric stresses are generally higher in oil or air than in the paper insulation. Unfortunately, oil or air has a lower breakdown stress than paper. For oil, it has been found that subdividing the oil gaps by mean of thin insulating barriers, usually made of pressboard, can raise the breakdown stress in oil. Thus, large oil gaps between the windings are usually subdivided by multiple pressboard barriers, referred to as the major insulating structure. Long vertical narrow sticks glued around the circumference of the cylindrical pressboard barriers maintain these oil gap thicknesses. The barriers are often extended by means of end collars curving around the ends of the winding to provide subdivided oil gaps at either end of the winding and strengthen these end oil gaps against voltage breakdown.

The minor insulation structure consists of the smaller oil gaps separating the disks and maintained by key spacers. Key spacers are narrow insulators, usually made of pressboard, that are spaced radially around the disk's circumference. Usually these oil gaps are small enough that subdivision is not required. Also the turn-to-turn insulation, usually made of paper, can be considered as part of the minor insulation structure.

Structural Elements

Under normal operating conditions, the transformer windings are under quite modest electromagnetic forces. However, the winding currents can increase 10-30 fold in a short-circuit fault, resulting in forces of 100-900 times normal since the forces increase proportional to the square of electric currents. The windings and supporting structure must be designed to withstand these fault current forces without any permanent distortion or damage. The current protection devices that are usually installed will interrupt the fault currents after a few cycles.

The coils are usually supported by thick boards of pressboard or other material covering the winding ends, which are called pressure rings. They have a center opening that allows the core to pass through. The rings are in the range of 1-4 inches for large power transformers. Since all the windings are not of the same height, some blocking made of pressboard or wood is required between the top of the windings and the rings. In order to provide some clearance between the high winding voltages and the grounded core and clamp, additional blocking is usually provided between the ring and the top yoke and clamping structure (Del Vecchio [1]).

Vertical tie-plates that pass along the sides of the core limb join the top and bottom clamps. These tie plates have threaded ends that are used to pull the top and bottom clamps together by means of tightening bolts, compressing the windings. These compressive forces are transmitted along the windings via the key spacers strong enough in compression to accommodate these forces. The clamps and tie plates are made of steel. Axial forces that tend to elongate the windings when a fault occurs will have to pull the tie plates in tension. Also since the coils and core are lifted as a unit through lifting hooks attached to the clamps, the tie-plates must be strong enough to carry the gravitational load. The tie plates are usually about 1 cm (3/8 in) thick. They are of varying width depending on the expected short circuit forces and transformer weight, and are often subdivided in width to reduce eddy current losses (Del Vecchio [1]).

The radial fault forces are countered inwardly by means of the sticks separating the oil barriers, and through additional support next to the core. The windings themselves, particularly the innermost one, provide additional resistance to inward radial forces. The radial force applied to the outermost winding is usually outward and puts the wires or cables in tension. Since there is no supporting structure on the outside to counter these forces, the material itself must be strong enough to resist these tensile forces.

There are also extra loads acting upon leads during a fault that are produced by the stray flux from the coils or from the nearby lead interacting with the current in the lead. Therefore, braces made of wood or pressboards that extend from the clamps are used to support the leads. This lead support structure can be quite complicated, especially if there are many leads and interconnections and is usually costume made for each unit.

The assembled coil, core, clamps, and lead structure are placed in the transformer tank using hooks attached to the top clamping frame (Figure 4). The tank serves many functions including containment of the oil for an oil-filled unit, protection of the coils and other transformer structures. It also protects personnel from the high voltages present, and keeps stray flux from getting outside the tank if made of soft (magnetic) steel. The tank is also made airtight to prevent air from entering and oxidizing the oil.

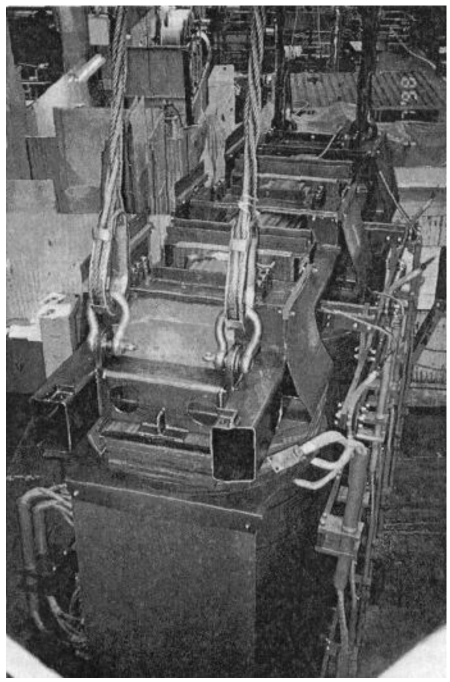


Figure 4. Top view of clamping frame for a 3-phase transformer (Del Vecchio [1]).

There are also numerous attachments to the tank such as bushings for getting the electrical power in and out of the unit, and transferring sensor information to remote processors and receiving control signals, and radiators with or without fans to provide cooling. There is a separate tank compartment on certain units for tap changing equipment. Also attached to some of the tanks over the top of the radiators are conservators. They are large, usually cylindrical, structures that contain oil in communication with the main tank oil (Del Vecchio [1]).

POSSIBLE FAILURE/DAMAGE MODES OF INTERNAL COMPONENTS

As previously mentioned, the internal components of transformer are mechanically designed to withstand substantial forces caused by fault currents. Hence, the internal components are generally expected to show a good behavior in resisting the earthquake excitations and transferring the loads to their core and avoiding structural damage. However, there are several modes of dynamic response that if excited during an earthquake event they can have adverse effect on electrical performance of the system, especially its long term performance. It should be also noted that design of transformers are proprietary and available data is very scarce. This is further compounded by the lack of uniqueness in transformer design. Thus, a challenge of this study has been always collecting reliable design information on internal packaging of substation transformers. Nevertheless, based on study of the structure and design of internal components using available limited and general literature, site visits to inspect an opened transformer, and discussions with technical staff of Southern California Edison and Los Angels Department of Water and Power along with limited information from past performance under earthquakes, the following probable failure modes are identified, which are explained in details in the sections that follow.

-Sliding of key spacers
-Movement or separation of leads
-Decrease or loss of safe clearance between layers of conductors due to their seismic excitations
-Loss of close fitting tolerances between limbs and yokes causing long-term electrical loss
-Flexural and rocking of core frame system

Sliding of Key Spacers

Under normal situation, the key spacers are under compressive pressure due to axial pre-stressing of the winding plus weight of the windings. However, ground motion and oil circulation can cause these spacers to slide. That is, vertical excitations can relieve the normal compressive force. Subsequently, two factors, namely the oil circulation between layers of winding and horizontal excitations caused by the earthquake can result in sliding of the key spacers. The oil used inside transformers has two functions, insulation and cooling. Convection is a source of movement of the oil inside the tank. In large transformers pumping of the oil through transformer might accelerate oil circulation. Hence, it is reasonable to assume that when pre-stressing is relieved, oil movement and/or horizontal vibrations can cause the key spacers to slide.

Loss of key spacers under the above scenario will result in lower spacing between vertically stacked layers of conductors. Closeness or perhaps even attachment of windings from different layers, which have different electric potentials, will interrupt the insulation design and can cause electric discharge.

Figure 5. Key spacers separating different layers of winding.

Movement or Separation of Leads

Leads coming from different parts of windings each have their own electric potential. They have differences in potential with all the other elements, and with the steel clamps and the tank that are of ground potential. Hence, they are well insulated and designed in a way to keep sufficient distance from all these other elements. To hold them in place, they are attached to a wooden frame built around the coil clamps. This frame is designed to carry their weight and the loads applied to them during fault currents (Del Vecchio [1]). If the connections of leads and the frame are compromised in any way resulting in their movement, the insulation design of the system could be jeopardized. Displacement of the wooden frame relative to the core can happen under seismic excitation due to differences in their frequencies. The core is a relatively stiff structure. The wooden frame, however, is much less stiff and may tend to have excessive displacement, thus, pulling the leads and applying an extra force on the connections. The picture in Figure 6 shows the leads and their supporting wooden structure.

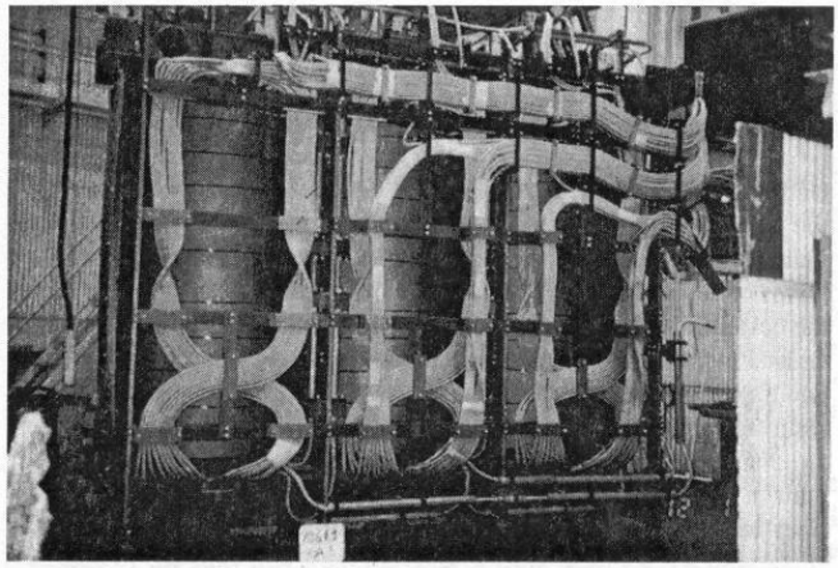


Figure 6. The wooden frame designed to support the leads (Del Vecchio [1]).

Design of the wooden frames and their connections to the leads is very case specific and depends on various components of the system ranging from its size to its structure and its voltage. For this reason and the facts that designers can easily develop a remedy and that its failure can be observed right away, no further work on this possible mode of failure is envisioned under this study at this time.

Decrease or Loss of Safe Clearance between Layers of Conductors Due to their Seismic Excitations

Windings at each level form a horizontal plane supported by key spacers where the distance/clearance between two layers is equal to the height of the key spacers. This clearance can be momentarily reduced due to vertical vibration of the layers of winding behaving as simply supported beams spanning between any two key spacers.

However, for two reasons it is not expected that this mode of possible damage is important. First of all, the winding has the same properties in different layers, except for small differences in the axial and radial electromagnetic forces applied to the winding. Therefore, it can be expected that all windings go through more or less the same response due to seismic excitation, thus, resulting in no relative displacement. The second and more important reason is that unlike the previous cases, even if loss of clearance happens, it is a momentary phenomenon that vanishes after ground motion ceases. It should be noted that the resistance of the insulation system to an electric potential difference is both a function of the magnitude of the potential difference and its duration. Hence, the same insulation that is sufficient for a stationary potential field will also be adequate under a higher potential difference in small fractions of time (Del Vecchio [1]). Therefore, it can be expected that the probability of any adverse effect under this situation is non-existent or quite minimal.

Loss of Close Fitting Tolerances between Limbs and Yokes

The core of transformers is one of the major sources of loss. One measure to reduce the core loss is using grain-oriented steel core. Any factor that causes the deviation of the flux from grain direction will increase the core loss. With the advent of modern steels with a very high degree of grain orientation, it requires the manufacturers to design cores with minimum discontinuity and change of the direction. To meet this design requirement it is common to use mitered corners at the connections of yokes and limbs. The mitered corners will limit the extent to which the flux path cuts across the grain direction at the intersection. At these mitered corners, the core laminates must be overlapped so that the flux can move to the adjacent face rather than cross the air gap that is directly in its path (Fig. 7). This fitting calls for very close tolerance of order of 0.5 mm to guarantee the electrical efficiency (Heathcote [2]).

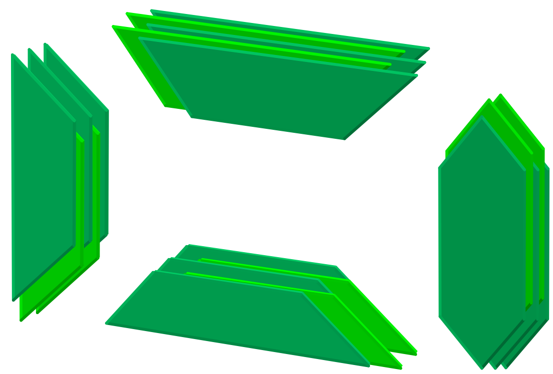


Figure 7. Idealized core laminations showing overlaps (not to scale).

Another design detail is that no bolts are used in the joints in order to enhance electrical efficiency; therefore, structural integrity of the core is maintained through prestressing. The top clamps (Figure 4) contain the top yoke while the tie-plates connecting the top and bottom frames apply prestressing force to the limbs and coils (Heathcote [2]). There is the possibility that the prestressing in the core is lost due to seismic forces. Loss of prestressing could result in loss of the close fitting tolerances at the yoke-limb joints. This can increases electrical loss, hence, decreasing the long-term efficiency of the transformer. Another possibility is that prestressing is partly lost due to aging, which is quite possible (Prevost, [3]). Subsequent excitations of the core lamination due to ground motion can cause small movements of the laminations, thus, compromising close fitting tolerances and affecting transformer longevity.

Furthermore, oil might penetrate through these momentary gaps, seriously impeding the electrical functioning of the core. Hence loss of prestressing can be regarded as the critical criteria for this mode of damage.

Flexural and Rocking of Core-Frame System

As previously mentioned, optimal electrical performance requires boltless design of core, which consists of thin sheets of steel laminations. On a large core this calls for a high degree of design sophistication to ensure that structural strength/rigidity is not compromised. Thus, manufacturers resort to clamping/prestressing to achieve this goal. Although this may provide adequate stiffness against gravity and fault forces, their integrity against dynamic vibration under earthquake ground motion should be investigated. Contact planes between the top yoke and limbs create a plane of weakness that can be jeopardized through dynamic vibration of the frame. Furthermore, the core-coil assembly is lower into the transformer tank and rests on the bottom plate without any mechanical attachments. There are gaps between core-coil assembly and the tank. The core-coil stability is maintained with wood blocks during transportation that are removed afterward. Thus, the entire core-coil system is quite susceptible to flexural and rocking modes of vibration that can cause pounding with transformer tank and impact with other electrical parts such as flux shunts/shields. Many of these behavioral characteristics may not cause an affect that has immediate impact on electrical performance; however, they will have significant impact on long term performance and longevity. As previously mentioned, LADWP has reportedly lost unexpectedly many transformers in the years after the San Fernando earthquake of 1971.

Currently these modes of possible damage to internal components are being investigated to quantify their relative importance. A major challenge is that transformers designs are very case specific and proprietary. Thus, available data are very scarce. However, using reasonable assumptions and engineering judgment based on available technical data it is possible to develop simplified analytical model for further study (Ashrafi, [4]). Such analytical models will allow the first of its kind study on quantifying the impact of earthquake ground motion on internal components of transformers. Furthermore, it will provide the mean to better evaluate justification of base isolation as a rehab scheme as discussed in a companion paper (Saadeghvaziri, [5]). It is shown that base-isolation can significantly reduce the inertia forces, thus, providing many benefits such as mitigating the adverse interaction between the transformer and the bushings and reducing the size of the foundation. Larger displacements associated with the use of base isolation are not so large that cannot be accommodated within the available design measures. Thus, it appears that base isolation is a viable rehabilitation strategy.

CONCLUSION

This paper deals with internal packaging of substation transformers, and discusses qualitatively the seismic response of transformer internal components. Several modes of possible damage due to dynamic response of internal components to earthquake ground motion are identified. Among modes of possible damage; sliding of key spacers, loss of close fitting tolerances between limbs and yokes, and flexural and rocking of core-frame system are identified as the most critical ones. Currently, the focus of this ongoing study is on response characteristics of internal components. The flexural and rocking mode of response can indeed be very important due to slenderness ratio of typical transformer. As discussed in a companion paper, Saadeghvaziri [5], the use of base-isolation has been identified as a viable technique to remedy this and other problems with seismic performance of substation transformers.

ACKNOWLEDGMENT

This research study is supported by the National Science Foundation under the Multidisciplinary Center for Earthquake Engineering Research (MCEER) program. The results and conclusions are those of the authors and do not necessarily reflect the views of the sponsors.

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