Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252

Vol. 33 No. 2 December 2016

The Impact of the Lack of Marine and Rail Standards on the Transportation of Large Power Transformers

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Abstract

Power transformers (>10MVA) are typically shipped from the factory by rail or marine cargo ship. In these harsh shipping environments, transformers are subjected to a variety of vibrational and impact forces. If these forces are too great, the transformers could be damaged, resulting in premature failure. There are few guidelines that describe best practices for monitoring, and, more importantly, mitigating such stresses when shipping transformers. Furthermore, manufacturers, railways, and marine shipping companies do not always have this information available, particularly for refurbished units. This paper discusses the impact this documentation drought may have for the affected parties.

Keywords

Transformer, rail, marine, shipping, vibration, impact, acceleration, pitch, yaw, roll

Introduction

With the aging of North America's power utility infrastructure, in conjunction with urban densification, a large percentage of generation, transmission, and distribution utilities (as well as industrial users) are purchasing large power transformers in ever-increasing numbers. But for many of these asset owners, the location of use for the transformer is many hundreds, if not thousands, of miles away from the manufacturing plant. Because of the weight or clearance restrictions on roadways, this often means transformers must travel to site by rail. Additionally, the manufacturing plant may be located overseas, which means that part of the transformer's journey is by marine vessel.

Transformer purchase specification documents provided to a manufacturer generally identify the specific electrical requirements that must be met, and usually include some form of reference to the external mechanical connections to the transformer, such as primary and secondary bus connections. However, the purchaser relies on the manufacturer to design and construct the internal components of the transformer. The challenge to the manufacturer lies with providing a transformer that is cost effective and suitable for the intended application, which would be easily facilitated if it could feasibly build the transformer on-site. However, the manufacturer must instead design and manufacture the transformer so that it will not only perform according to the end-user's specifications, but also withstand the various environmental conditions and mechanical forces it would be subjected to during transportation to the site.

Although it is essential in the course of designing and transporting power transformers to consider appropriate protective measures against environmental factors, such as weather and corrosive marine environments, these factors are outside the scope of this paper. Instead, it focuses on the various acceleration forces applied during transportation and the dynamic response of the transformers due to such forces.

The Transformer Market

According to data obtained from the United States International Trade Commission Interactive Tariff and Trade DataWeb[1], between 2010 and 2015, the United States imported nearly 1,200 large power transformers (>10MVA) per year, with an annual value totaling more than $1 billion, from around the globe, including North and South America. More than 500 of these units were imported from Europe and Asia alone, so the assumption could be made that nearly half of all imported

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power transformers were exposed to the marine shipping environment*.

Similarly, in Canada, between the years 2011 and 2015, the import market for large power transformers averaged more than $180 million annually[2]. Although no specific data was available regarding the actual number of units, based on the import data for the United States, it could be estimated that approximately 200 units were imported annually from other countries — with approximately 40% from outside North and South America (where railcar or truck would be considered the primary method of transportation to site).

With the utility and large industrial electrical infrastructure in North America continuing to age, it is expected that the importation of large power transformers will continue to occur in the foreseeable future. Although it is difficult to obtain information regarding the percentage of power transformer damage claims where the failure can be directly attributed to transportation, it is the author's experience that this number is statistically significant — at least with respect to total loss value.

As will be discussed later in this paper, there are a number of standards and guidelines in place to guide manufacturers and shippers in the proper care and handling of a power transformer; however, it is the author's experience that the manufacturers do not generally adhere to the specifications contained in these documents. As a result, it becomes very difficult to accurately identify transformer failures that can be attributed directly to transportation. In addition, it is likely that these statistics will not change significantly in the future, unless the transformer industry makes a concerted effort to comply with (and maintain) these standards.

The Transportation Environment

The transportation environment for large power transformers is harsh, since it subjects transformers to forces that are not normally experienced during their operational life. These forces include vibration, impact, pitch and roll, and extreme weather conditions, all of which can be detrimental to the life of a transformer and must be accommodated for by the transformer manufacturer.

Figure 1 shows the primary acceleration forces that may act on a transformer during transportation†.

Mode of Transportation	Forces	Event Triggers
Truck	Vibration Impact	During movement During onload / offload
Rail	Vibration Impact	During movement Switching activities During onload / offload
Marine	Vibration Surge, sway, and heave Pitch, yaw, and roll Impact	During movement During movement During movement During onload / offload

Figure 1
List of primary acceleration forces experienced during various modes of transport.

For reference purposes, **Figure 1** includes the acceleration forces experienced during truck transport. However, because most transformers larger than approximately 25MVA exceed the weight and size restrictions of standard transport trucks‡, this paper focuses on the primary modes of transport for these larger transformers — namely railcar and marine vessel. Although similar forces are present in each of the different transportation environments, this paper will evaluate the rail and marine environments separately.

Although **Figure 1** includes impact forces during onload and offload to trucks and railcars, the risk of impact is significantly reduced from that on a marine vessel. This is primarily because of the open sides of trucks and railcars that provide full visibility for the crane operator. On the other hand, transformers are often placed in the holds of marine vessels, where they are at risk of impacting the sides of the hold. This risk is further increased where the crane operator does not have full visibility below decks and relies on the stevedores for guidance via radio communication and hand signals.

Rail Shipping: The Methods of Transport

Rail transportation of transformers occurs via one of three main methods. The choice of method is dependent on the size, and, more specifically, the clearance and weight of the equipment. These methods include:

* This assumption ignores the possibility that a certain percentage of these transformers may have been transported by aviation carrier — a method that is generally considered too expensive for large power transformers.

† Forces shown are expected during normal operating conditions. This table does not include abnormal conditions such as vehicular impact during transportation.

‡ Specialized trailers with multiple independent axles are often used to shuttle these large transformers between the railcar and the pad; however, their use on public access roads is generally restricted. In addition, their operating speed is slow enough to mitigate most of the detrimental acceleration forces.

1. Standard flatbed railcar
2. Low-ride flatbed railcar
3. Schnabel car

Only the smallest of power transformers will meet the clearances when loaded on a standard flatbed railcar. This is partly because there are often many low bridges along the track route; therefore, height restrictions can be quite severe. Midsize power transformers (up to ~90T) are usually loaded onto heavy capacity flatcars, which have lower loading decks and additional axles to handle the heavier loads. Transformers weighing more than 90T require special railcars known as Schnabel cars, which have multiple axles and use the transformer itself as part of the car. The two sections of the Schnabel car shown in **Figure 2** would be separated in the middle and the transformer inserted between the support arms.

The transformer must be protected against both vibration and impact when shipped by rail. Various vibrational forces are applied against the transformer while the train is rolling. The intensity of these vibrational forces is influenced by a number of factors, including track quality and bearing wear.

Impact forces normally peak during switching activities of the rolling stock. Switching activities can impose significant longitudinal forces on a transformer and its internal components.

Figure 2
Unloaded Schnabel car parked on a siding. The transformer would be inserted between the two support arms.

Marine Shipping: The Methods of Transport

Transportation of transformers by sea vessel usually involves a combination of transportation modalities, as the manufacturing plant and/or the final destination for the transformer may not necessarily be located close to a port. With this in mind, however, the primary focus of this paper with respect to marine transportation of transformers is from the time the transformer is craned onto the vessel until the time it is offloaded.

A transformer is most at risk of severe impact during the time of onload and offload, while suspended underneath the crane. This impact can be lateral (from hitting the vessel wall during maneuvering) or vertical (due to high-speed contact with the ground or vessel bottom when lowering). Impacts during onload and offload can be as high as 10*g*, particularly when maneuvering the transformer during high winds.

During vessel movement, the transformer will experience both high-frequency (vibrational) and low-frequency (roll/pitch/yaw) motions. The high-frequency mechanical forces on a marine vessel are caused by the operation of the engines and generators used to drive the vessel. Low-frequency forces are exerted as a result of the vessel's response to the movement of the ocean.

A Look at the Forces Involved

Whether shipping a transformer by rail or marine vessel, it must be protected against excessive vibration (high- and low-frequency) and impact. **Figure 3** provides data regarding the estimated acceleration forces that may be applied to a transformer during rail and marine shipments[3]:

Mode of Transport	Longitudinal	Lateral	Vertical
Rail (Combined Transport)	1.0*g*	0.5*g*	1.0*g*
Marine (Unrestricted)	0.4*g*	0.8*g*	1.0*g*

Figure 3
Estimated acceleration forces during transport.

It is important to note that there is also an inherent frequency associated with each of the acceleration forces described in **Figure 3**. It is not just the forces, but also the frequencies of these forces, that affect the transformer and its components. This frequency is related to the critical duration (or minimum event duration) below which damage will not occur. Critical duration is discussed later in this paper.

The Standards

Manufacturers can refer to a number of generic standards and guidelines when designing and manufacturing a transformer to be shipped by rail or marine vessel. The Association of American Railroads (AAR) publishes a number of guidelines, standards, and regulations pertaining to the safe transportation of various types of cargo by rail.

The International Maritime Organization (IMO) correspondingly publishes similar guidelines for safe transportation of cargo via marine vessel. Another organization, the American Bureau of Shipping (ABS), publishes similar rules, guides, and regulations; however, these pertain primarily to life safety and security of property in the context of ship design, construction, and operation.

The issue at hand is that the shipping industry created the noted standards. In 2010, the International Council on Large Electric Systems (CIGRÉ) started a Working Group (WG A2.42), comprised primarily of members representing the large multinational transformer manufacturers[4], to look into this matter. The mandate of this working group included the preparation of a brochure guide on transformer transportation, which would provide useful information to transformer manufacturers regarding the withstand forces and times that might be imposed on a transformer during various modes of transportation. According to the CIGRÉ website, this working group completed its mandate in 2012 with a presentation to the Study Committee A2 on Transformers. A search by the author found no evidence that the brochure was ever published.

The Institute of Electrical and Electronics Engineers (IEEE), which is an industry association (as opposed to an industry standards organization such as the International Electrotechnical Commission or the International Standards Organization), has an active standards development community, and regularly publishes standards relating to various issues within the electrical and electronics industry. With respect to the topic of this paper, the relevant published standard is C57.150-2012, *IEEE Guide for the Transportation of Transformers and Reactors Rated 10,000 kVA or Higher*[5]. This comprehensive document provides designers, manufacturers, and shippers with a number of items that should be considered when transporting a transformer. Although this is an important industry standard, manufacturers and shippers are not required to conform to the provisions in the document. Therefore, items will inevitably be ignored due to cost or other restrictions.

Finally, FM Global, one of the world's largest insurance and risk management providers, published *Property Loss Prevention Data Sheet 5-4 "Transformers"*[6]. This document provides guidance primarily to asset owners regarding loss mitigation techniques (from an insurance perspective) with respect to transformers. It includes a very short section on transportation of transformers, which states only to install multiple impact recorders and to perform Sweep Frequency Response Analysis[§] (SFRA) before and after shipping. The *Data Sheet* includes no other information that may help mitigate transportation losses.

The Data Problem

The challenge with investigating transportation damage of large power transformers depends upon the amount of test and monitoring data available from the time of factory acceptance testing until the incident. In many cases, the manufacturer only performs its standard battery of electrical tests during the factory acceptance procedure. These tests prove that the transformer will perform according to the specification requirements, but they do not provide any information as to the physical characteristics of the transformer's internal components.

In most cases, only one or two impact recorders are installed on the transformer to monitor transportation conditions. These can typically be configured in one of two ways:

1. Setpoint trigger, wherein data is recorded at levels above a specific value;

2. Regular sampling interval, where data is recorded at regularly timed intervals, regardless of the value.

Some of the more advanced impact recorders allow recording of both modes simultaneously, while others will maintain a temporary data buffer and log a certain amount of time on either side of a significant event. The premium models of impact recorders also contain a GPS receiver, and will provide real-time data monitoring and alarming during the entire voyage.

Both types of monitoring methods mentioned above have advantages and disadvantages. The first type — recording only significant events that are

§ The SFRA applies a low-voltage sine wave to each individual coil within a transformer. The sine wave is applied across a large spectrum of frequency — from a few Hertz to several MHz. Because the windings of a transformer coil are separated by a layer of paper insulation, each winding exhibits different resistive (R), inductive (L), and capacitive (C) properties, thereby creating a complex electrical filter that passes some frequencies and mitigates others. Each injected frequency, therefore, will generate its own response at the output of the coil, based on the electrical filtering characteristics of the windings.

greater than a setpoint value — will identify potentially significant impacts, but this data does not provide any indication about the amount or frequency of vibration experienced by the transformer during the rest of the voyage. The second recording method — regular sampling — may capture vibration levels and frequencies, but risks missing potentially significant impact events. This is why it is important to use an advanced model capable of hybrid data recording.

Impact recorders, if properly utilized, are sufficient for rail transport. They are also important for marine transport in two capacities. First, they are critical during the onload / offload phase, when the transformer is at higher risk of impact while being maneuvered by the crane. Secondly, an impact recorder capable of monitoring vibration is necessary to capture the high-frequency vibration exposure of the transformer during operation of the marine vessel.

A second key device is essential for monitoring the transformer while onboard a marine vessel: an inclinometer. Because impact recorders are sensitive only to high-frequency events (including impacts), they do not capture low-frequency events, such as the pitch, roll, and yaw experienced on a ship. These events can be just as detrimental to the coils of a transformer as an impact or vibration, and it is just as essential to capture these as well as impact events.

The Missing Test

One test that provides excellent information about the geometry of transformer coils is SFRA. When performed before shipping — and again after installation of the transformer — the two SFRA graphs can be superimposed. If the two curves line up, this is a good indication that the transformer windings did not incur physical damage during transportation. If a shift is observed between the two curves, then it becomes important to conduct further visual and electrical examinations in order to verify the operational integrity of the transformer.

The Investigation Challenge

The fragility of a transformer is determined by its weight, internal configuration and construction, and the presence of either permanent or temporary internal shipping braces. Because of the complexity of these devices, it is not possible to establish a "typical baseline" of resistance to impact and vibration through simple verifications, such as drop testing or shaker table analysis. Furthermore, theoretical analysis — even with the use of modern 3D software models — is difficult. The forensic engineer, therefore, must rely on the manufacturer's knowledge, experience, and historical data for similar transformers when evaluating the fragility (or alternatively the toughness) of a transformer.

Case Studies

There are many variables that can lead to transformer damage during transportation. This paper will present three case studies wherein the transformers were subjected to excessive forces:

1. Transformer #1 –
   Vibration damage during rail transport:
   The transformer was shipped by rail from the manufacturing plant to the customer's site in another province. Upon arrival at the customer's site, damage was observed on some of the transformer components, and an insurance claim was filed.

2. Transformer #2 –
   Impact/incline damage during marine transport:
   A newly refurbished transformer was shipped from the manufacturing plant by truck and then by marine vessel to Canada. During offload from the marine vessel, the surveyor observed the transformer strike the sidewall of the vessel hold.

3. Transformer #3 –
   Excessive vibration during rail transport:
   A new transformer was shipped by rail from the manufacturing plant to the customer's site in another province. Upon arrival at the customer's site, the manufacturer noted high levels of vibration were logged by the impact recorders, and commenced a transportation damage claim against the rail company.

Each case study will evaluate the forensic engineer's observations and the data that was available to the forensic engineer in the course of the investigation. The forensic engineer's analysis of the data and resulting conclusions will then be presented, along with the challenges encountered in the course of the subject investigation.

**Transformer #1 –
Vibration Damage During Rail Transport**

In this case, the subject transformer was shipped by rail to the customer's site. Upon arrival, the customer observed damage on the transformer and filed an insurance claim. The forensic engineer was mandated on behalf of the manufacturer. The shipper, whose liability was limited by the contract terms, did not assign an expert.

Upon arrival at site, the forensic engineer reviewed the impact recorder data, and determined that the unit had sustained a number of significant acceleration events. Further inspection by the engineer also revealed several damaged internal components.

When evaluating the potential effects of an acceleration force on a transformer, the forensic engineer must identify both the intensity of the applied force as well as the duration. Together, these values provide an indication of the energy content applied to the transformer during an event. Exceeding one value or the other may not necessarily cause damage to the transformer. However, if both values are exceeded during the same event, the forensic engineer should expect to find damage.

In this case, the transformer manufacturer had provided specific maximum acceleration intensity limits to the shipper. Also included in these limits were values of critical impact duration for the subject transformer. Mathematically, the relationship between intensity and duration is expressed as follows:

$$If\ t_e < t_c\ or\ a_e < a_c\ then\ damage\ will\ not\ occur.$$

$$If\ t_e > t_c\ AND\ a_e > a_c\ then\ expect\ to\ find\ damage.$$

$$where:$$

$$t_e\ is\ event\ duration\ (s)\ t_c\ is\ critical\ duration\ (s)$$

$$a_e\ is\ event\ acceleration\ \left(\frac{m}{s^2}\right)\ a_c\ is\ critical\ acceleration\ \left(\frac{m}{s^2}\right)$$

In the subject case, two identical impact recorders were installed on the transformer, both mounted next to each other on the top of the transformer tank, as shown in **Figure 4**.

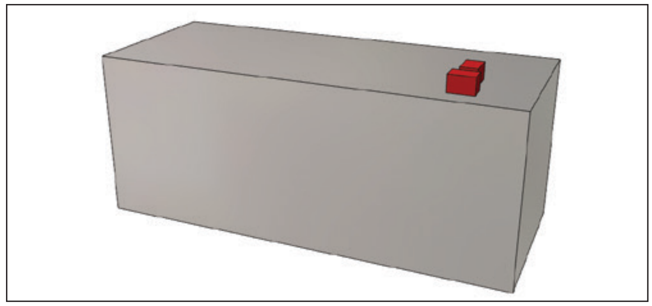

Figure 4
Transformer showing location of impact recorders.

Figure 5 shows the relationship between the recorded acceleration intensities and the critical duration values for each of the four significant events identified by the forensic engineer.

Event	Acceleration Intensity	Duration
#1	IR1 $a_e > a_c$ IR2 $a_e < a_c$	IR1 $t_e > t_c$ IR2 $t_e < t_c$
#2	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e > t_c$
#3	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e < t_c$
#4	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e < t_c$

Figure 5
Actual event vs. critical value.

In the first event, Impact Recorder #1 (IR1) logged acceleration and duration values greater than the specified limits, while the same event logged by Impact Recorder #2 (IR2) was below both limits. IR2 logged a second event as exceeding both critical values, while IR1 logged the same event below both values. Subsequently, IR2 logged two additional significant events that exceeded the critical acceleration, but the critical duration was too short. Because the critical duration of the last two events was below the threshold specified by the manufacturer, the forensic engineer deemed them not to have harmed the transformer. Instead, the focus of the investigation was placed on the circumstances surrounding the first two events.

Upon arrival at site — and due in part to the recorded impacts — a representative of the manufacturer undertook an internal inspection of the transformer**.

During this inspection, the representative discovered several pieces of pressboard that were loose or completely dislodged from their mounting locations. Additionally, he also found several internal securing bolts to be loose, in addition to a number of other cracked, broken, and abraded components within the transformer, including fragments of magnetic debris on the tank floor.

** The forensic engineer was not present during this examination and relied on notes and photos provided by the manufacturer's representative for this portion of the investigation.

The forensic engineer worked with the manufacturer to evaluate the cause of damage to the transformer. Based upon the limited data available, neither party could determine, with any accuracy, the root cause for any of the damage incurred to the internal components of the transformer. With this in mind, however, the following hypotheses were postulated:

- The recorded impacts, excessive vibration, or both, may have cracked the internal components;

- The magnetic debris most likely resulted from metal-on-metal contact that followed the breakage of another component and subsequent vibration of the metallic parts during the remainder of the journey;

- Vibration probably caused the pressboard to become displaced.

Because of the limited data available during this investigation, neither the forensic engineer nor the manufacturer's design engineers could determine a probable cause for the damage to this transformer. Although the impact recorder data provided evidence of significant acceleration events that exceeded the manufacturer's specifications, the forensic engineer had to rely on the manufacturer's information and design engineers' expertise with respect to the fragility of the transformer and the potential effects of the recorded shock events.

Since the impact recorders were mounted side by side, the logged data should have been similar between the two devices; however, the forensic engineer observed significant differences between the two data sets. Because the damage to the transformer was evident, the forensic engineer accepted the significant event data as valid, and did not perform any further verification on the data. A Nyquist analysis may have explained the differences between the two data sets and provided validation of the differing data; however, this would be a topic for a future research paper.

Because he was mandated on behalf of the manufacturer, the forensic engineer was able to work closely with the manufacturer's design engineers to properly understand the design parameters of the transformer. The fragility data (acceleration and critical duration limits) provided by the manufacturer greatly assisted the forensic engineer in determining the correlation between the impact events and the damage to the transformer components. Although the exact sequence of events could not be accurately identified (and may have only been possible with internal and external time-stamped video monitoring), the availability of vibration monitoring data and fragility data made this investigation as close to an ideal case as could reasonably be expected.

Transformer #2 –
Impact / Incline During Marine Transport

In this case, the subject transformer was shipped by truck and marine vessel to the customer's site. After it had been in service for some time, the owner noticed an issue with the transformer operation and filed an insurance claim. The forensic engineer was mandated on behalf of the manufacturer; another expert investigated the claim on behalf of the truck transport company. Marine surveyors were present during the onloading and offloading of the transformer from two separate marine vessels, and their reports were provided to the forensic engineers to aid in their investigations.

The subject transformer was an 88 MVA rectifier transformer that the European manufacturer had refurbished. After the refurbishment was completed, the manufacturer shipped the transformer by truck from the manufacturing facility to a shipping port, where it voyaged by ocean vessel to Canada. Upon arriving in Canada, the transformer was offloaded from the ocean vessel to continue its journey to the site.

Prior to leaving the manufacturing facility, the transformer was fitted with two impact recorders, as shown in **Figure 6**. The data logs from these impact recorders showed that this transformer experienced two significant impact events during its voyage. The first occurred on the truck after leaving the manufacturer — where it sustained damage to a bushing cover and grounding link cover that were situated on top of the transformer when it failed to meet the clearance under an overpass. A second incident occurred when

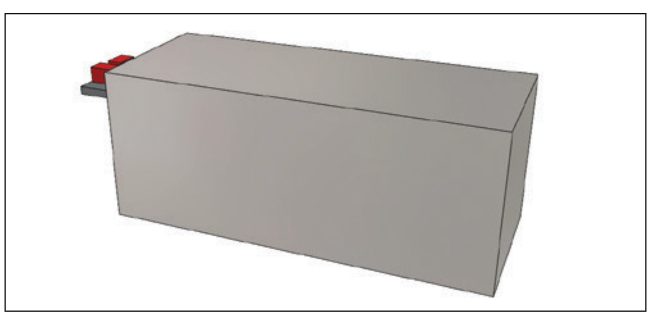

Figure 6
Transformer showing location of impact recorders.

the transformer impacted the side of the vessel during offloading, as shown in **Figure 7**. This impact event was observed and logged by the marine surveyor, whose report was used by the forensic engineer as evidence for his investigation.

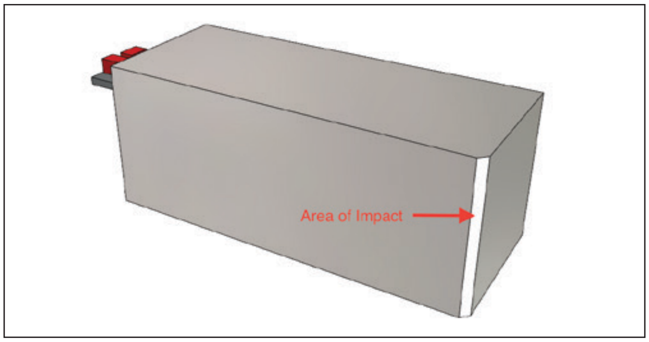

Figure 7
Transformer showing location of impact in white.

The forensic engineer reviewing the logs from the two impact recorders found two anomalous events. The first event, recorded while the transformer was on the truck, was an excessive impact in the vertical (z) axis. Only fractions of a *g* acceleration were recorded in the transverse and longitudinal (x and y) axes, likely due to the normal deceleration of the truck and the location of the impact recorders. The forensic engineer confirmed this event by correlating the impact recorder logs with the driver's logs.

The second event was an anomalous acceleration in the transverse (x) axis. Unfortunately, the impact recorder logs provided to the forensic engineer only indicated the acceleration in each direction; the duration of these events was not available. Therefore, the forensic engineer could not calculate or otherwise determine the energy content of the impacts associated with either event.

As discussed previously, the shipping industry has developed (most likely through empirical data) a set of values that comprise the maximum acceptable accelerations to which a transformer can be exposed without damage. As part of the investigation, the forensic engineer asked the manufacturer for information about the subject transformer; however, the manufacturer indicated that it "had no data regarding the maximum *g* force acceptable for that transformer." Instead, the manufacturer had relied on the industry standard high limit of 5 *g*. The implication, in this case, was that the manufacturer had not determined the maximum level of acceleration that the transformer could withstand, nor did it provide such information to the transporters.

As described in Section 8.3.2 of IEEE C57.150-2012, there are six degrees of motion that a transformer may experience when onboard a marine vessel. These fall into two categories: linear or axial motion, which includes surge (longitudinal), sway (lateral), heave (vertical), and rotational motion, which includes roll, pitch, and yaw. Impact recorders would normally be used to capture linear motion, while inclinometers would be necessary to capture rotational motion. Inclinometers were not attached to this transformer; therefore, the forensic engineer could not assess the intensity of low-frequency motion to which the transformer was exposed in the pitch (x), roll (y), or yaw (z) axes nor determine their possible effects on the transformer.

Following the commissioning and energization of the transformer, the owner observed internal gassing. Using an infrared imaging camera, they discovered a hot spot near one of the mounting feet for the core and coil assembly, as shown by the red spot in **Figure 8**. The owner conducted an internal inspection of the transformer tank and provided photographs to the forensic engineer. After analyzing the photographs, as well as construction drawings of the transformer core assembly, the forensic engineer subsequently determined that the core assembly had shifted within the tank, placing one of the three mounting feet too close to the tank wall. This physical shift changed the electrical dynamics of the transformer, which led to arcing activity between the core assembly and the tank wall.

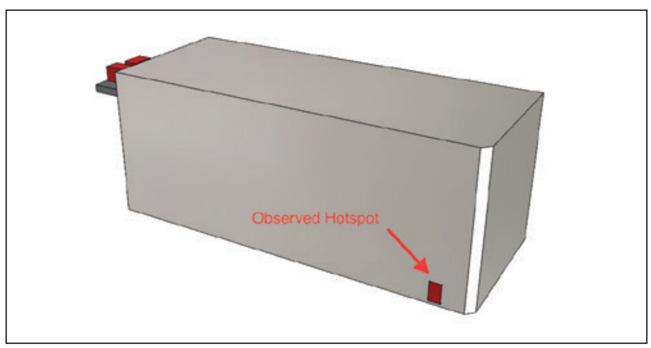

Figure 8
Transformer showing location of hot spot.

The manufacturing shop drawings of the transformer revealed that the core assembly was permanently attached to the tank lid. If constructed properly, this configuration ensured that the internal tolerances would have been very tight with respect to the resting location of the core assembly on the tank floor once the lid was installed. Based on this information, the forensic engineer determined that the probability of the core assembly being misaligned during insertion into the tank was very low — therefore, the misalignment at the base of the core assembly would have occurred during the transportation of the transformer.

Because the impact recorders were mounted near one top corner of the transformer— and the observed damage was to the opposite corner — it is reasonable to believe that they did not record significant accelerations during the offloading impact. The concept of angular velocity dictates that the closer the impact recorder is to the pivot point of the transformer, the smaller the acceleration it will log. It may have been possible to extrapolate the acceleration forces applied to the opposite end of the transformer during this event; however, a second set of impact recorders installed at the end closer to the impact would have logged a more accurate value of acceleration, as well as provided an additional data set for validation. Despite the logged acceleration values being within acceptable limits, based on the analysis of the marine surveyor's report and the events following the detection of the hot spot, the forensic engineer deemed it reasonable to believe that the transformer was damaged, at least in part, by the impact with the sidewall of the marine vessel.

Additionally, the lack of inclinometers installed on the transformer during the ocean voyage left a large data gap with respect to angles of inclination of the transformer. Due to the core assembly being mounted toward the top of the transformer, even a moderate angle of inclination might have caused the core assembly base to shift within the tank. Without this data, the forensic engineer could not determine if the misalignment of the core was a result of excessive inclination of the transformer during the ocean voyage.

Based on the previous example — and in light of the limited amount of data available from the voyage of the transformer — the forensic engineer could not identify a root cause of the core assembly displacement with a high degree of certainty. Notwithstanding, the following possible events led to the displacement of the core assembly from its original configuration:

- The core assembly shifted as the result of excessive angle of incline of the transformer during the ocean voyage;
- The core assembly shifted due to reduction of friction forces caused by high-frequency (engine) vibration during transport;
- The core assembly shifted during the impact sustained when the transformer contacted the ship wall during offloading.

Because the impact recorders were both mounted adjacently near a top corner of the transformer (which was close to the pivot point), the sensors recorded minimal levels of acceleration forces, which were applied transversally at the opposite end of the transformer when it impacted the sidewall of the ship. Furthermore, it is also possible that the core assembly could have slipped during movement of the ship in heavy seas.

In this case, the best evidence to indicate that the transformer had been damaged during transportation was the marine surveyor's observation of the transformer hitting the sidewall of the marine vessel during offloading. Because the impact recorders did not log an anomalous event due to their mounting location relative to the impact location, the data did not provide much assistance to the forensic engineer during his investigation, which was further hindered by the lack of transformer incline data.

Observations of the physical displacement of the transformer core assembly, along with the marine surveyor's report, provided enough evidence to the forensic engineer that the transformer had been damaged at some point during the voyage from the plant to the site. However, due to lack of data, he could not accurately identify whether the damage occurred on land, on the marine vessel, or during marine shore-handling operations.

Transformer #3 – Vibration During Rail Transport

The subject transformer was a new 300 MVA substation transformer shipped by rail from the manufacturing plant, with a short road journey by multi-axle transport truck from the rail siding to the substation (approximately 3km away). Prior to offloading from the railcar, the manufacturer's representative visually inspected and observed no damage to the exterior of the transformer.

Prior to shipping from the factory, two impact recorders were mounted on the top of the transformer (one at each end, as shown in **Figure 9**), with a third mounted directly on the railcar; however, the location and orientation of this one was not known. Once the transformer railcar was parked on a siding near the substation — and before the transformer was offloaded to the multi-axle transport vehicle — the manufacturer's representative downloaded and reviewed the impact recorder data, noting high levels of vibration. However, none of the recorders logged any significant impacts. Because of the high levels of vibration recorded by the impact recorder, the manufacturer put the rail transporter on notice for potential damages to the transformer, pending an internal inspection and electrical testing. The forensic engineer was mandated directly by the rail transporter. A marine surveyor also attended the site investigation along with the manufacturer's technician.

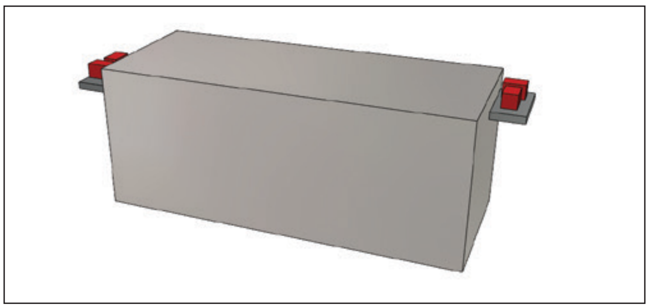

Figure 9
Transformer showing locations of impact recorders.

Due to space restrictions within the tank, only the high-voltage side (HV) of the transformer was accessible. From this side, the forensic engineer and manufacturer's representative conducted a visual inspection of the transformer core, the HV coils and taps, and the tertiary voltage (TV) windings. Because of these internal space restrictions and working at height regulations, only the manufacturer's representative could visually inspect the low-voltage (LV) windings, which was done by looking through an access hatch on top of the transformer.

During the internal inspection, the forensic engineer found all blocking and bracing to be in place and secure. Of particular note were the cushioning pads under the transformer core, which were of considerable interest due to the high levels of vibration recorded by the impact recorders. The forensic engineer noted that these were still in place under the core, and remained secured to the pins that extended out of the transformer core. The forensic engineer also found spacer blocks on the outside of the core sections were still in place and secure, and the cords used for securing internal components were still under tension and did not show signs of wear. Another key area susceptible to vibration damage was the insulation between the high-voltage windings; however, the forensic engineer did not observe any indications of abrasion, puncture, or cracking due to vibration.

Because the transformer was not completely assembled at the time of the examination, a limited number of electrical tests could be performed to confirm the operational state of the windings. In the case of this transformer, the manufacturer's representative conducted only an insulation resistance test, the results of which were consistent with the expected values for a new transformer. Based on the insulation resistance test, the manufacturer's representative determined that the coils were not damaged during transportation. The manufacturer did not indicate whether they performed an SFRA test on the transformer prior to it leaving the factory, but this test was not performed on-site.

In the case of this transformer, the core assembly was secured to the floor of the transformer, and appeared to be generally freestanding inside the tank, with some lateral bracing to maintain the stability of the top of the assembly. The forensic engineer determined that this was one of the main reasons the core assembly was able to withstand the high levels of vibration incurred during transportation.

Since neither the forensic engineer nor the manufacturer's representative observed damage to the internal transformer components — and the insulation resistance test results were acceptable — the transformer manufacturer closed the claim against the rail transporter. Because the manufacturer acted quickly in closing its claim against the rail transporter, it did not provide the impact recorder data to the forensic engineer, nor did the forensic engineer have an opportunity to determine if the manufacturer had calculated values for the fragility of the transformer.

Based on the internal examination and discussions with the manufacturer's representative, the forensic engineer determined that despite the high levels of vibration logged by the impact recorders, the transformer was not damaged during transport. The working hypothesis for this was that there was sufficient internal bracing and other protective measures, which reduced the fragility of the transformer so that it could withstand high levels of vibration.

As previously discussed, although the manufacturer indicated that significant levels of vibration were detected, they did not indicate which impact recorder logged the high levels of vibration, nor did they provide the actual data logs from the impact recorders. Although still an interesting case study in the capabilities of transformers to withstand significant levels of vibration, having the actual vibration data in hand would have provided hard evidence to support the theory that not all "significant events" recorded by impact recorders necessarily lead to transformer damage.

Conclusions

Because of the unique and complex nature of transformers, significant barriers exist to calculating the response of a given transformer to external stimuli within a reasonable degree of engineering certainty. Manufacturers rely on their experience and knowledge of transformer construction in order to design and manufacture the units to survive the journey to the customer's site. The author believes that many manufacturers rely on shippers to "handle with care," but do not necessarily understand the dynamic forces encountered during shipping, nor do they provide fragility values to the shippers. In many cases, this simply means that transformers are designed and constructed with large safety factors. There are software programs that can assist transformer manufacturers with modeling external forces; however, these programs do not provide all the answers, and still require significant experience and input from the design engineer.

Despite the availability of published standards pertaining to both design and shipping of large power transformers, transportation incidents regularly cause damage to the internal and external components of transformers. Sometimes the damage is the result of mishandling that impacts a transformer well above its withstand capability. Other times, the acceleration forces are below the acceptable thresholds, but due to other (often unknown) factors, the transformer still incurs damage.

When investigating transportation damage claims, the forensic engineer must obtain all available design, test, and monitoring data from the transformer manufacturer and shipping companies. It is in the best interest of the forensic engineer to examine the design, construction, and shipping conditions of the damaged transformer in order to develop a thorough comprehension of the fragility of the transformer and the forces that acted upon it to cause damage.

Until the holy grail of transformer modeling is discovered, manufacturers must rely on their knowledge, experience, and a bit of luck when shipping their transformers by rail or marine vessels. This knowledge and experience must continue to come from empirical data obtained from actual transformer transportation projects – those with and without significant events. The only way to obtain this data is to install as much monitoring equipment as is economically and technically feasible on the transformer – and the vehicle – and then analyze the data. This should be done in conjunction with SFRA tests before and after shipping so that even minor deviations in the transformer winding structure can be correlated with the transportation event data. As such, until the utility industry officially adopts a minimum standard of required testing, monitoring, and handling procedures for transformers, forensic investigators must rely on their own experience in finding the root cause hidden in the large data gap.

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