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Logistics Risk Management in the Transformer Industry

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Abstract: Transformers often are shipped thousands of miles, involving multiple handoffs, and more than a dozen logistics teams before they are installed. With an impact threshold of about 2.5g, damage isn't always evident. Hidden damage may trigger an event cascade that causes catastrophic failure long after installation. Impact monitors reduce that potential by recording the impact and duration of potentially damaging events. Prior to transformer installation, this data can be compared to the transformer damage boundary to determine the extent of potential damage. This data enables improvements in risk management practices that, by properly ascribing liability, can identify where and when damage occurred and ultimately reduce warranty costs and transformer downtime.

In 2014 an electrical transformer being shipped from Israel to Canada was damaged in transit. The $2 million transformer was returned to Israel for repair then shipped back to the client, delaying the project. The insurer sued the railway and the logistics carrier for $911,233 in damages. It settled for $750,000 on behalf of its client.

In a 2013 case (ABB Inc. v. CSX Transportation), when a $1.3 million transformer was "allegedly damaged" in transit, a U.S. appeals court reversed a portion of a lower court ruling and made the railroad liable for the full damages of $550,000 rather than the $25,000 liability it expected under the Carmack Amendment to the Interstate Commerce Act. CSX has never admitted liability.

These cases are notable, but not the only examples of accidents that cause delays in transformer delivery and installation. Simply attaching impact monitors to the shipments could have improved both of those situations. These important risk management tools would have shown the extent, duration, and location of the impacts quickly and easily, helping prove liability for some rather substantial repair bills.

Logistics is a Vital Part of Transformer Health
Consider this: the supply chain for transformers stretches around the globe, involving multiple handoffs, transportation methods, and carriers. Each handoff entails risk.

The transformer for the substation at Conway, New Hampshire is a case in point. The 411 ton transformer was built in Hebei, China, 7,000 miles from its destination. It traveled by truck and rail from Hebei to the port of Xingang, where it was loaded onto a ship. It crossed the Pacific, transited the Panama Canal, entered the Gulf of Mexico and stopped in Houston. It then entered the Atlantic and steamed up the East Coast before being off loaded at Searsport, Maine onto a Schnable rail car. Designed for tight turns, the Schnable car uses hydraulics to shift the load left or right to ensure clearances.

From Maine, the transformer went by rail through Quebec, Canada, and returned to the U.S. through Vermont before reaching North Conway, New Hampshire. There, it was transferred to truck for its final journey to the Conway Power Station.

That convoluted route was necessary to ensure the infrastructure could support the 411 ton transformer. Still, it crossed 84 bridges. Some of those hadn't borne heavy freight in 26 years. In all, more than 15 service providers were involved in transporting the transformer and ensuring the safety of the route.

What Can Go Wrong?

Such a complex transportation plan and long supply chain requires meticulous planning. Each transfer increases the risk. Although the Conway, NH delivery was executed smoothly, other transformers have broken free and damaged other goods. One even fell off its transport car. Several court cases cite "damage" or "alleged damage" during transport.

A drop of even a few inches can damage transformers. The heavier they are, the greater the potential for damage. (Damage is determined by weight, volume and impact surface, and also by the amplitude, duration, and frequency of the impact.)

The resulting damage may be visible or, more concerning, concealed. If concealed, these transformers may be installed and made operational, triggering failures during power up or even later in their life cycle. That damage may never be tracked back to its source, causing great expense for power utilities or manufacturers through no fault of their own.

One instruction manual (from manufacturer WEG) for dry transformers, for example, cautions handlers to lift the transformer only by specific points. Using others could severely damage the transformer. Forklifts aren't recommended, either, and strains may only be applied to the base beams or core pressing beams. It points out that transformers with protective boxes shouldn't be lifted using the eyebolts on the outside of the box. Instead, it can be lifted using the leach eyes on the transformer's top beams inside the box.

It also cautions against transporting or storing the transformers if they were subjected to "abnormal vibrations and occasional collisions."

> *"When damages occurs in remote parts of the world, shipping the damaged transformer back to the manufacturer isn't always a valid option."*

Impacts and vibrations can:

- Loosen nuts and bolts, causing overheating.
- When panels are loosened, it also can create excessive noise and create resonance among components. Abrade insulation, leading to short circuits and damaged windings.
- Distort or displace windings, loosening their clamping pressure, which contributes to their collapse during electrical faults.
- Reduce clearances between the housing and components.
- Damage related components, like radiators and bushings. Harden metals.
- Create micro fissures in the transformer.

It's bad enough when this damage occurs in geographically accessible locations. When it occurs in remote parts of the world, shipping the damaged transformer back to the manufacturer isn't always a valid option. Instead, a repair team may need to fly in at great expense.

Where Damage Occurs

An analysis showed that large power transformers (>100T) get damaged between the 2.5 to 5.0 g (2-20Hz) band, while small equipment like a laptop gets damaged between 37 to 50 g (2-250Hz) band.

That means that most damage to transformers occurs at low acceleration levels during transit. This damage is most likely from loading, unloading, and rigging operations, and during transportation. A small portion of damage occurs as transformers are positioned on their foundations.

When unloading and rigging accidents occur, the impacts are in the range of 1 to 10gs in the 2-20 Hz band.

Mechanical shocks while on trailers are related to braking and road conditions. They typically range between 0.5 and 1 g in the 3-350 Hz band, and are unlikely to cause damage. On trains, transformers experience longitudinal impacts up to 4 g in the 2-20 Hz band from shunting operations, and vertical shocks between 0.5 and 1 g in the 2-500Hz band from rail joints.

Aboard ships, transformers experience rolling, pitching, and yawing, with low-frequency vibrations typically ranging between 0.3 and 0.8 g in the 2-30 Hz band. These vibrations rarely cause damage. However, the pitch and roll of the ship can reach up to 5-7 degrees and 45 degrees respectively, which can loosen cargo and send a 100T transformer crushing into other cargo.

Damage is based on the combination of acceleration (g), duration (msec), and frequency (Hz). Impact monitors typically record acceleration and duration to help users pinpoint the potential for damage, and where and when it occurred. Frequency may be extrapolated from the duration of the impact.

Impact Recorders

Impact recorders won't prevent the damage, but they can alert you that transformers have experienced mechanical impacts or vibrations above certain thresholds and, therefore, may be damaged.

IEEE guide C57.150 specifies two recorders per transformer, mounted diagonally opposite each other. The impact recorders are mounted on opposite ends of the transformer because transformers are becoming so long in length. If one end of a transformer is dropped, the recorder on the opposite end would not record the true acceleration value because the transformer would attenuate the acceleration value from one end to the other.

The point of this recommendation is to support preinstallation analyses that are more efficient and more accurate. If engineers know the transformer they are checking experienced an impact that exceeded a certain threshold – usually about 3Gs – they know to check carefully for damage that may otherwise be missed.

Likewise, if they can prove the transformer was handled carefully and experienced no impacts even approaching the thresholds where damage occurs, they may be able to streamline the analysis.

"Impact recorders won't prevent the damage, but they can alert you that transformers have experienced mechanical impacts or vibrations..."

By using impact monitors, customers know to check for visible and hidden damage before these transformers are installed. And, if damage has occurred, impact recorders also help attribute liability.

The most advanced impact recorders record the acceleration of impacts, their direction along x, y, and z axes, event duration, tilt and roll, vibration, geographic location, and time of occurrence. They typically record hundreds of impact events for well-over a year with accuracy of plus or minus two percent, and report in realtime or near-real time through wireless networks.

Because these impact recorders are tamper proof, they are accepted as evidence by courts of law and are trusted by insurance companies. Impact monitoring also can help reduce warranty claims from failures once the transformers are in operation.

Damage isn't always evident. Micro fractures in internal components, for example, may not be noticed, but may cause problems (such as overheating) long after the transformer has begun operating. Or small, unnoticed issues may create a cascade that ultimately results in catastrophic failure. When hidden damage goes unnoticed, the power utility or manufacturer end up paying for damage that occurred on the transportation carrier's watch. This is damage that should be covered under the carrier's insurance. Proper use of impact monitors, however, helps inspectors uncover hidden damage and attribute it to the responsible party.

For carriers, impact monitors can help limit their liability by ascertaining exactly where, during transit, the damage occurred. With multiple handoffs to carriers in many countries and widely varying logistics practices and infrastructure conditions, knowing whether transformers were damaged on your watch, or before or after you took possession, can be invaluable in managing risk and transportation partners.

For example, several carriers have argued they aren't liable for damages because they took reasonable care. However, in Prima (et al) vs. Panalpina, a lower court found in 2000 Panalpina liable for damages when an electrical transformer came loose during transit and damaged other cargo. That court cited Panalpina's promise to Westinghouse: "Rest assured your shipment will receive, door-to-door, our close care & supervision." An appeals court overturned the decision, saying Panalpina was a forwarder, not a carrier. That distinction aside, with impact monitoring, you can determine whether "reasonable care" was taken, because you have the impact data.

Using impact monitors also helps engineers better estimate transformer fragility without resorting to shock response spectrum analysis or finite element analysis. Monitors provide real-world, experiential data that can be accumulated, analyzed, and correlated to specific conditions, carriers, or transformer designs.

Conclusion: Impact recorders are part of a cohesive risk management strategy that stretches from manufacturing to installation. Transformer health depends on accurate, reliable data – including data that measures impacts that can cause damage. Impact monitors provide that data, thus helping to increase the accuracy of preinstallation analyses, saving time and money.