Medium Voltage Cast-Resin Transformers for Crane Applications

Application Number: AP-09
Date: October 2013
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  e.g.:

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  • Trained or instructed according to the latest safety standards in the care and use of the appropriate safety equipment.

  • Trained in rendering first aid.

There is no explicit warning information in this documentation. However, reference is made to warning information and instructions in the Operating Instructions for the particular product.

Reference regarding export codes

AL: N

ECCN: N
Foreword

Objective of the application

This application note was created for the purpose of assisting Siemens employees and in particular, end-users in understanding how Siemens cast-resin type transformers meet the requirements of IEC60076-11:2004, and have been designed for optimum performance within crane drive systems. The application note shows the design used for Siemens medium voltage cast-resin type transformers which are used to step the voltage supplied to the crane infeeder down to a useable level.

Structure of the document

The documentation of this application is divided into the following main parts.

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<tr>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Notes</td>
<td>This section contains the legal information relating to the relationship between Siemens and the user of this document.</td>
</tr>
<tr>
<td>Foreword</td>
<td>Contains a statement of the goal of the application note, as well as a brief summary of the document structure.</td>
</tr>
<tr>
<td>Medium Voltage Cast-Resin Transformer Visual Overview</td>
<td>For the purpose of introduction to the topic of GEAFOL transformers, this section contains some visual aids on the topic.</td>
</tr>
<tr>
<td>Background of GEAFOL Transformers &amp; Operational Qualities</td>
<td>Includes some qualitative information on GEAFOL cast-resin transformers, their advantages and their application within crane drive infeeder circuits.</td>
</tr>
<tr>
<td>Specification Guideline for Cast Resin Transformers for Crane Drive Systems</td>
<td>Contains technical data relating to transformer design, installation and operation.</td>
</tr>
</tbody>
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Medium Voltage Cast-Resin Transformer Visual Overview

Figure 1: Main Components of Cast-Resin Transformer

Figure 2: Potting of the Winding in the Vacuum Furnace
Figure 3: Partially Potted HV Winding with Magnified Cross-Section of Laminated Aluminium Winding

Figure 4: Radial-Flow Fans Increase Performance by up to 50%

Figure 5: Top View of Single Leg of Cast-Resin Transformer Showing Iron Core Painted With Blue Corrosion Resistant Paint, Low Voltage Windings Separated by Spacers, the Fully Completed High Voltage Winding, and the Red Finish of the Epoxy Resin and Quartz Powder

Figure 6: Flammability Test on a GEAFOL Transformer
Background of GEAFOL Transformers & Operational Qualities

The History of the GEAFOL Transformer

For crane drive systems initially oil immersed transformers were used, however due to the safety and environmental consequences which accompany the use of oil immersed transformers (such as leakage, explosion and ground water pollution), it is now recognized that cast-resin transformers offer clear advantages.

The cast-resin transformer was first developed in Germany in the 1960s. From 1969, Siemens and AEG produced transformers in the joint company “Trafo Union”. Currently GEAFOL transformers cover an output range from 50kVA to approximately 50MVA with operating voltages up to 52kV. Figure 7 shows a diagram of the development of the power requirement from 1966 to 2015, operating voltage and rated lightning impulse voltage. The sole reason for this is the approach taken by Siemens through all of the company’s work, and that is one which places the quality, performance and safety of the product first.

![Figure 7: Development of GEAFOL Transformers from 1966-2015](image)
The Materials Used/ Production Process

The core of a cast-resin transformer is constructed from ferromagnetic iron. To reduce the losses due to eddy currents, iron laminations are stacked together to produce the core material, instead of using one large crafted piece of iron. GEAFOL cast-resin transformers typically use laminations of thickness 0.3mm, which yields standard no-load losses. Lower available thicknesses yield a lower magnitude of no-load losses. For instance, 0.27mm are available, as well as the smallest thickness of 0.23mm for end user who desire minimum no load losses in their system (in particular wind power applications), however for crane applications, the standard thickness of 0.3mm is normally used. This iron core will be painted over in a corrosion resistant paint which is effective against salty air that is present in the marine environment of harbour cranes.

The low voltage winding is installed closest to the core. This winding effectively consists of a malleable aluminium sheet. Aluminium is chosen as conductor material due to the coefficient of expansion of aluminium which is close to that of epoxy cast-resin, hence reducing stresses within the transformer. The mounting geometry between the secondary winding and core determines the coupling capacitance for the secondary winding to ground. This capacitance is a relevant parameter for minimizing the impact of common mode voltage stress for motor windings for drive systems with self-commutated pulses line-side converters (ALM).

Table 1: Comparison of Thermal Expansion Coefficients of Aluminium, Copper and Epoxy Cast-Resin

<table>
<thead>
<tr>
<th>Coefficient of Thermal Expansion</th>
<th>Pure Aluminium</th>
<th>Copper</th>
<th>Epoxy Cast-Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 25°C (Room Temperature)</td>
<td>23.1</td>
<td>16.6</td>
<td>35</td>
</tr>
<tr>
<td>@ 120°C</td>
<td>70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The low voltage turns of the transformer are glued together by a synthetic insulating material. It is important to note that the use of aluminium for use on the windings of the transformer also poses an advantage in terms of the final weight of the transformer. After winding some of the low voltage sheet winding around the core, a gap is allowed before finishing the winding process. This gap contains spacers which promote ventilation within the core, and as a result reduce core temperature and lengthen the lifespan of the device.

In comparison, the coils of the high voltage winding are made of aluminium foil. This type of winding offers a large benefit in terms of electrical safety, due to the reduced resulting electrical stress. Above all, this approach to setting up the high voltage windings (which is shown in Figure 3) lends itself to high power frequency and impulse withstand voltage. One of the most influential factors that affect the life time of a transformer is the level of partial discharge that occurs within the epoxy resin-quartz powder mix, once it has been completely cast-an effect which causes dielectric breakdown of the installation, and will be explored in the next section.

Other notable factors about the design of a GEAFOL transformer are the inclusion of PTC thermistors within each of the core legs and the low voltage winding, and the exclusion of a screen winding between the low voltage and high voltage coils. The purpose of temperature monitoring using thermistors is for the function of emergency stop which is necessary in the situation where the temperature of the low voltage winding increases too high due to the current level. It is also important to be aware that the screen winding is not permitted on GEAFOL transformers for use on cranes as it increases the capacitance between the secondary winding and ground and thus increases the amplitude of common mode oscillation, which causes voltage stress for the motor installation.
Partial Discharge
As mentioned briefly above, the effect which is known as partial discharge (PD) may occur in electrical insulation systems and causes dielectric breakdown of the material. The insulation material may be gaseous, liquid or solid- however in order for partial discharge to occur, this material must contain voids (for example, an air bubble which has dried into the epoxy insulation of a dry type transformer), which experience a high voltage stress. Over time, the effect can grow and erode the electrical insulation.

The cause of partial discharge is the difference between the dielectric constant of the insulation material (in this case epoxy cast-resin), and the gas within the bubble/void (most likely air filled). The majority of potential air bubbles are prevented from forming within the insulation by potting the high voltage windings of the transformer with epoxy resin under vacuum at a high temperature- hence, excluding a sizeable amount of unwanted gasses within the insulation in the form of dried in bubbles. This is one of the key reasons why on average, the lifetime of a GEAFOL transformer is 30+ years.

The principle of partial discharge is that the dielectric constant of the air bubble within the insulation is lower than that of the insulation itself. This will result in the presence of a large electric field across the gap, and in the case where a high voltage stress exists across the gap, a discharge will occur. This results in dielectric breakdown, which can eat away the insulation and cause serious damage over time.

When the phenomenon of partial discharge occurs, pulses of current will appear for a short period of time. The magnitude of this current is very small and its duration is usually in the region of nanoseconds to milliseconds. If these high frequency pulses are seen to occur, the effect of partial discharge can be identified- however due to the small magnitude of the pulses the effect is sometimes difficult to spot.

The effect of this discharge is energy dissipation in the form of heat, sound and light. By taking the effort to minimize this effect within the transformer insulation (via potting of the H.V. winding in a vacuum), a longer lifespan is guaranteed for the transformer.

Figure 8: The Process of Partial Discharge
Behaviour of GEAFOL Transformers/ Safety Warnings

The reasons why GEAFOL are the best option for your application are as follows:

- Aside from the high level of performance of a GEAFOL design in fire conditions, it is also humidity-proof, tropic-proof and low-noise.
- GEAFOL cast-resin transformers are the ideal solution for cranes where the crane mechanical design leads to high load densities and placement of the power sources close to the drive system. Using a GEAFOL transformer eliminates the need for a special room for containment of the device, as the installation of power sources close to the load is perfectly acceptable.
- GEAFOL have a long history of application to cranes. The design is flame resistant and self-extinguishing. Hence, in the case of an external fire, the transformer will extinguish immediately once the source of energy is removed. The products created during a fire on a GEAFOL transformer are not toxic what so ever - in fact the products are the same as those created by a regular domestic fire. The fire behaviour class of the design is F1. This is the highest rating of fire behaviour class; however it is still possible for accidents to occur if the transformer is not properly maintained/installed. Shown below are two very rare incidents which have occurred quite recently:
Figure 11: GEAFOL Transformer installed in Australia

Figure 12: GEAFOL Transformer installed in New Zealand
In the case of the incident in Australia, from Figure 11 there may not appear to be anything wrong with the transformer shown, however upon closer inspection of the W phase (shown on the left of the photograph) damage to the upper surface is evident. It is presumed that heavy contamination was the cause for this discolouring of the transformer surface. It is thought that this contamination was subject to sparking from the transformer which ignited the contaminants and caused the burning shown in Figure 11. This is one of the reasons why it is important to continue maintenance of the transformer throughout operation. Simply cleaning the surface of the transformer at regular intervals would have resulted in prevention of this incident.

Clearly the damage which has occurred to the GEAFOL transformer in New Zealand is a lot more extensive - as shown in Figure 12. It is thought that a fire originated at the central leg of the transformer due to a loose connection- highlighting the importance of correct installation of the device. The resulting damage is both severe and widespread, effecting the insulation of all three of the windings, the delta connected H.V. terminals, the upper and lower parts of the transformer frame and even the L.V. cables on the other side of the transformer which have been affected by wind driven fire. Despite the self-extinguishing nature of the transformer, a fire stemming from an installation fault will spread rapidly across the transformer. The result of course of this incident was the replacement of the transformer which implied a large expense for the user.
Comparison/Contrast Between Different Transformer Types

Table 2 illustrates the main similarities & differences between GEAFOL, oil immersed and dry impregnated type transformers:

Table 2: Comparison of GEAFOL Cast-Resin Transformers and Other Transformers

<table>
<thead>
<tr>
<th>Feature</th>
<th>Oil Immersed</th>
<th>GEAFOL Cast-Resin</th>
<th>Dry Impregnated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place of Installation</td>
<td>Outside installation as per VDE 0101.</td>
<td>Easily integrated anywhere regardless of the application/environment. Inside, underground, upper floors in buildings, outdoors.</td>
<td>Inside dry, dust free rooms primarily. Installation at high humidity, aggressive atmospheres or outdoors is also possible; however considerable efforts must be made in terms of protection measures.</td>
</tr>
<tr>
<td>Behaviour During Fire</td>
<td>An oil transformer exposed to flames is very dangerous and can have explosive consequences.</td>
<td>Fire behaviour class F1 (highest). Both flame retardant and self-extinguishing. Only 5.5% of the transformer material is flammable.</td>
<td>Can also attain a fire behaviour class of F1.</td>
</tr>
<tr>
<td>Voltage Ranges</td>
<td>Can be designed for all voltage levels (especially for very high voltage application, however low and medium voltage designs are also possible.</td>
<td>Medium to high voltage applications.</td>
<td>Low voltage applications (Ratings up to 400kVA).</td>
</tr>
<tr>
<td>Pricing</td>
<td>Generally cheaper than dry type transformers.</td>
<td>Approximately 120% that of an equivalently rated oil immersed transformer. (Somewhat negligible in comparison to total cost of entire crane).</td>
<td>Very difficult to attain an environmental class of E2 when designing a dry impregnated transformer, especially at higher voltages (e.g. 20kV, 30kV etc.) Environmental Class may only reach E1, or transformer may not achieve any Environmental Class whatsoever.</td>
</tr>
<tr>
<td>Environmental Impact</td>
<td>Oil immersed transformers are known to leak and pollute ground water.</td>
<td>Environment class E2 (highest). Frequent pollution/condensation/both simultaneously. 94% of transformer is recyclable.</td>
<td></td>
</tr>
</tbody>
</table>

Version VX.X0
<table>
<thead>
<tr>
<th>Feature</th>
<th>Oil Immersed</th>
<th>GEAFOL Cast-Resin</th>
<th>Dry Impregnated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatic Performance</td>
<td>Indoor installation only. Humidity build up in oil causes regular oil changes to become necessary.</td>
<td>Climate class C2 (highest). Outdoor installation down to -25°C. Humidity-proof and tropic-proof.</td>
<td>Dry impregnated transformers are weaker to humidity than GEAFOL transformers. The noise level of a dry impregnated transformer can reach levels equal to oil immersed and GEAFOL transformers as the main source of noise is the iron core, which is common to both GEAFOL transformers and dry impregnated transformers.</td>
</tr>
<tr>
<td>Noise Level</td>
<td>Low-noise.</td>
<td>Same noise level as oil immersed transformer due to spacers used for the purpose of vibration insulation.</td>
<td></td>
</tr>
</tbody>
</table>
Application of GEAFOL Transformers on Cranes

The infeed transformer is a vital part of the crane infeeder circuit. It provides the function of stepping down the value of supply voltage to a value which is more usable by the components within the crane drive system. Figure 13 shows a detailed circuit diagram of the infeeder circuit of a crane, clearly displaying the infeed transformer in the upper portion of the infeeder circuit. In reality the infeeder is a 3-phase circuit, with one secondary winding wound around each of the transformer legs. There is a reduced voltage across each of these secondary windings, for the purpose of operation of the low voltage infeeder. Hence, Figure 13 is somewhat simplified as it just shows on single phase, with the transformer having one primary and one secondary, whereas in reality, everything downstream of the transformer primary exists three times-duplicated for each of the other two phases in the same circuit configuration shown below.

The effect of inrush current is eliminated within the infeeder circuit due to the use of a pre-charging resistor and contactor. Hence, the transformer will not be damaged upon motor start up due to currents which are multiple times higher than the normal operating current, as this current will be limited to a safe value. The maximum efficiency of a GEAFOL transformer can be greater than 99% if the power factor is equal to 1. This maximum efficiency occurs at 40-50% transformer charge.

Figure 13: Detailed Circuit Diagram of Crane Infeeder Circuit Showing Infeed Transformer
Sizing Instructions

For crane applications Siemens recommends to size the transformer based on the total RMS power demand for the circuits supplied by the transformer. The resulting required RMS power requirement is to be multiplied with a safety factor to arrive at the required rated apparent power (kVA) of the transformer.

As outlined in other sections of this document crane drive transformers may be exposed to high stress with regard to saturation and winding heat-up. It is therefore recommended to specify “converter duty” features.

Therefore, the above mentioned safety factor is recommended to be set to:
- 1.1 for Siemens GEAFOL cast resin converter duty transformers
- 1.2 for all other transformers

When designing/purchasing a transformer, it is necessary to know both the altitude and the ambient temperature at which the transformer will be operated. The higher the installation point of the transformer, the less dense the air and hence the weaker the cooling ability of the air. This means that the higher the transformer is installed, the larger the unit must be. A similar issue arises for a high ambient temperature. The higher the ambient temperature at the point of installation, the larger the unit will be. Transformer designers do not concentrate on derating factors to be applied in the case of excessive altitude/ambient temperature. Instead, the issue of importance is to know the ambient temperature and altitude at the point of installation and design the unit for this case.

<table>
<thead>
<tr>
<th></th>
<th>Motion 1 (e.g. hoist)</th>
<th>Motion 2 (e.g. trolley)</th>
<th>Motion 3 (e.g. gantry)</th>
<th>Motion 4 (e.g. slow)</th>
<th>Total RMS power</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>RMS kW per motor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>No. of motors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Total RMS power (kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Efficiency IR (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Efficiency MOT (J)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Total RMS power (kVA)</td>
<td>kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Auxiliary (kVA)</td>
<td>kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Derating factor (1.1 for GEAFOL, 1.2 for others)</td>
<td>Total required power kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Selected transformer rating (kVA)</td>
<td>kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Ratio of overload to selected kVA</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Altitude where the Transformer is used</td>
<td>m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Ambient temperature</td>
<td>°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Ambient temperature factor</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Selected transformer rating (kVA) @ ambient temperature / altitude</td>
<td>kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14: Sizing Instructions for GEAFOL Converter Duty Transformer
Housing Instructions

<table>
<thead>
<tr>
<th>Installation</th>
<th>Indoors</th>
<th>Indoors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of protection</td>
<td>IP 00</td>
<td>IP 23</td>
</tr>
<tr>
<td>Environmental conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locked electrical locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water up to 60° to 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct sunlight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt-laden atmosphere</td>
<td></td>
<td>Special paint</td>
</tr>
<tr>
<td>Corrosive chemical environment</td>
<td></td>
<td>Special paint</td>
</tr>
<tr>
<td>Accidental contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foreign bodies &gt;12 mm dia.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prodding with wire</td>
<td></td>
<td>On request</td>
</tr>
</tbody>
</table>

Figure 15: Housing Options

Figure 15 shows different housing options. An IP00 installation must be accompanied by a protective fence. IP23-I housing is the alternative for indoor installation. These are the two forms of housing used for a transformer in a crane drive infeeder circuit.

Figure 16: Cross-Section of Ventilation Slots
The images shown in Figure 16 and Figure 17 are representations of the ventilation slots used on housing systems. Figure 16 gives a close-up view of the ventilation slots used on the cover of an IP23 housing design for indoor application. The image shown in Figure 17 however, is that of a Prod-Proof design. For a complete guideline of the requirements which accompany the use of IP00/ IP23 housings on GEAFOL transformers, it is necessary that EN 60204-11 “Safety of machinery - Electrical equipment of machines - Part 11: Requirements for HV equipment for voltages above 1000V AC or 1500V DC and not exceeding 36kV” is both consulted in detail and followed carefully, so that both the functionality and legality of the installation is guaranteed.
Temperature Monitoring

For the purpose of temperature monitoring of the low voltage windings, Positive Temperature Coefficient (PTC) thermistors are installed on the windings. As this is the most economical solution, PTC thermistors are used in crane systems for this function, however for other applications, PT100 resistance temperature detectors or capillary tube thermistors are used. Due to the rectifier and inverter downstream of the transformer in a crane infeeder circuit, a “converter transformer” must be used for crane applications, to safeguard the transformer core against overheating and destruction during drive system failures it is recommended to install temperature monitoring of the core.

Three phase transformers, such as those used in crane drive systems contain a temperature monitoring system consisting of 3 PTC thermistors in series with a tripping device (one thermistor per phase). In the present configuration, one PTC is used for the temperature sensing of each core leg and two PTC thermistors are used for each low voltage winding (one for warning and one for tripping).

Effectively the operation of the configuration is as follows. The circuit diagram of the temperature monitoring system is shown below in Figure 20. As was previously stated, PTC thermistors are installed on the low voltage windings and within the core. The relationship between the resistance of a PTC thermistor and the temperature of the device is non-linear. In fact the relationship could be approximated as a large instantaneous rise in resistance once a certain temperature (the tripping temperature) is reached. An example of this relationship is shown in Figure 19. Once this step in resistance occurs when the tripping temperature is reached, the 3RN1022-1DW00 thermistor motor protection tripping unit causes the contactor to change position. Conversely, once the temperature of the thermistor falls to approximately 3K below the tripping temperature, this contactor returns to its previous position. As an alternative to PTCs, PT100 platinum temperature resistors can be used for the purpose of temperature monitoring of the transformer windings which have a resistance of 100 ohms at 0°C.

**Figure 19:** Temperature-Resistance Relationship of a PTC Thermistor
Figure 20: Temperature Monitoring and Tripping System for Cranes

Core Saturation & D.C. Bias

Every transformer will undergo saturation if the flux contained within the core is too high. Effectively the occurrence of core saturation in a transformer implies that if the magneto motive force (MMF) is increased, a proportional increase in flux (Φ) will not be observed. Both alternating current and direct current can cause saturation within the transformer core. In the case when the primary current/voltage is excessive, it is possible that the core of the transformer will saturate during periods in the AC cycle when the voltage/current is at a peak. When this occurs, the output from the secondary side of the transformer will no longer be sinusoidal.

Another cause of transformer core saturation is operation at frequencies lower than the rated design value - for instance in the case when a transformer designed for 60Hz is operated at 50Hz.

As per Faraday’s Law:
\[ V = N \frac{d\phi_i}{dt} \]

- Where voltage and flux (Φ) are sinusoidal functions.

\[ \phi_{Peak} = \frac{V_{Peak}}{N(\omega)} = \frac{V_{Peak}}{(N)(2 \pi f)} \]

Hence, it is clear that flux within the core arising from a sinusoidal voltage will also have a sinusoidal profile. This equation also displays the inverse relationship between flux and voltage. This is because a certain level of flux is needed within the core to create enough voltage to oppose the primary voltage. Hence, if the speed of operation is slowed (i.e. 60Hz to 50Hz), then it will be necessary for the flux within the core to rise to a higher level during a peak, so that this voltage can be maintained. Depending on the transformer and the magnitude of the frequency drop, saturation may occur due to this increase in core flux.

However it is also important to note that DC current flowing in the transformer winding can cause core saturation. A direct current component within an alternating current input to a transformer will increase the flux within the core. As shown below in Figure 21, it effectively shifts up the alternating flux within the core by a fixed amount. Hence, during a peak of the flux waveform, the saturation limit will be closer than without any D.C. component. Conversely however, during a trough (low point) in an A.C. cycle, the flux will be brought farther from saturation.
Figure 21: Possibility of Saturation Increases with D.C. input component

Figure 21 above shows the effect that DC current flowing in the windings of a transformer has on the flux within the core. Effectively, the sinusoidal flux profile is offset by the DC value, with the flux now oscillating about this value, having peaks closer to saturation, and troughs farther from saturation.

However, in a crane infeeder circuit how does this DC current arise? Within an infeeder using an ALM or an SLM (shown below in Figure 22), regeneration is possible. Regeneration is effectively the return of energy from the line module back to the supply system. Within an ALM/SLM, there are IGBTs which are controlled via Pulse Width Modulation (PWM).

Figure 22: ALM/SLM Receiving 3 Phases of Power

In a crane infeeder circuit, the process of Pulse Width Modulation is used within the line module (rectifier for the purpose of shaping the line current. The width of these pulses (i.e. the duration of time for which they are applied) is variable, and is controlled so that the current waveform entering the infeeder is as smooth and sinusoidal as possible. An example of the method of operation is shown in Figure 23 below.
Figure 23: Example of Pulse Width Modulation in an Inverter (Upper Image (Blue): Output Sinusoid from Inverter, Lower Image: Pulses of Voltage Applied to IGBTs)

The output in blue which is clearly not a perfect sinusoidal waveform, approximates one (the red waveform). However, the application of DC voltage pulses to the IGBTs can result in DC regeneration within the system, which implies that DC current will be present in the transformer windings, bringing the core closer to saturation. An imbalance between the voltage-time-area applied during positive and negative half cycles causes a direct current component flowing into the transformer. Hence, as stated above this will bring the core of the transformer closer to saturation, effectively shifting the sinusoidal flux profile higher by a constant value—which is indicated in Figure 21 as the “flux centreline”. As shown below, the level of pulsed voltage during a positive half cycle and negative half cycle are not always equal. This imbalance in voltage will result in excess DC current flowing into the infeed transformer secondary.
But what DC current levels are actually permitted within transformer windings? As a general rule, as long as the level of DC current is below 0.5% of the nominal current of the transformer, there should be no issues under normal operational procedure. However once this level is exceeded and the DC current rises to between 0.5% and 1% of the nominal transformer current, some issues will arise in terms of transformer noise, heating of the core and an increase in harmonics within the no load current. DC currents higher than 1% of transformer nominal current should be avoided. It is also possible to design transformers to be able to minimize serious problems.

Below, a case study of two GEAFOL transformers is shown illustrating their fire behaviour characteristics:
Skin Effect
Skin Effect refers to the unequal distribution of current within a conductor. Effectively, when skin effect is prominent within a conductor, the current density at the surface is higher than at greater depths into the conductor material. Hence, the majority of the current flows at or near the “skin” of the conductor.

Figure 25: Skin Effect in a Cylindrical Conductor- Red Shading Indicates Current

For transformers supplying self-commutated pulsed regenerative rectifiers the possible impact of high frequency current components on the transformer secondary winding is to be considered. In normal operation the converter’s filter circuits will keep high frequency currents to a minimum. Potentially critical though is the case of the failure of such a filter circuit as this may lead to substantial amplitudes of high frequency currents loading the windings.

As shown in Figure 25, the symbol $\delta$ denotes the skin depth. At high frequency operation, skin effect reduces the effective cross sectional area of the conductor by reducing the skin depth. This phenomenon can occur within transformer windings when carrying A.C. current. Compare this to a conductor carrying DC current which does not undergo this uneven current distribution. Despite from the fact that aluminium has a similar thermal expansion coefficient to that of epoxy cast-resin, another benefit of using aluminium is that the thermal conductivity of the material is such that it helps to distribute temperature across the winding material evenly, so that hot spots on the winding are mostly avoided.

The phenomenon of skin effect is synonymous with systems using alternating current. The effect originates from the alternating magnetic field which is produced due to the alternating current flowing through the conductor. This changing electric field generates an EMF which works to counteract the change in current. This EMF forces the electrons which make up the A.C. current outwards from the centre of the conductor, hence reducing current density at the centre of the conductor and increasing current density near the “skin” of the conductor. Linked with the presence of skin effect is eddy current loss.
Forced-Air Cooling
The rated power of a transformer can be increased by up to 50% by using the technique of forced cooling. This method is only suitable for transformers of initial power rating up to 2500kVA. The process of forced-air cooling is carried out by the installation of centrifugal/ radial flow fans, as shown in Figure 4 and below in Figure 26. The installation procedure entails fitting 2/3 fans on each longitudinal side of the transformer mounting. The operation of the fans is triggered by a control device, which measures temperature.

![Figure 26: Centrifugal-Flow Fans on GEAFOL Transformer (Green)](image)

Despite the increase in power rating, there are some drawbacks to installation of fans on GEAFOL transformers:
- Increased power losses
- Increased space taken up by the transformer
- Due to the need for uninterrupted air flow at the LV coil, LV connections must be redesigned.

The fans which can be installed rotate via a single-phase AC induction motor, and the noise level from the devices is restricted to the range of 71-74dB. From an economic perspective, for transformers of power rating below 400kVA, it would be cheaper to use a larger transformer as opposed to using a transformer equipped with fans, which is rated within this range. Within the acceptable power range for usage of fans on a transformer (as previously stated, this is up to 2500kVA), the price of fans and associated control devices is roughly constant, which of course means that for a larger transformer, the use of fans becomes a more attractive option.
Overload Conditions
Figure 27 shows the permissible duration for a certain overload, for various levels of loading:

**Figure 27: Overload Duration verses Percentage Overload for Various Load Percentages**
Specification Guideline for Cast-Resin Transformers for Crane Drive Systems

The following table details the main specification items for Siemens GEAFOL drive transformers along with comments made during the meeting in Kirchheim. Figures are for an example of a supply voltage of 11.4kV, 60Hz:

Table 3: Specification Guideline for Cast Resin Transformers for Crane Drive Systems

<table>
<thead>
<tr>
<th>Type</th>
<th>Siemens GEAFOL</th>
<th>Comment/Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing standard</td>
<td>4GJ63</td>
<td>IEC60076-11; IEC60076-11:2004</td>
</tr>
</tbody>
</table>
| Environmental, climate and fire class | E2, C2, F1     | **E2** - No space heaters are required. Consistent condensation or pollution or a combination of the two may occur in an outdoor installation. *(Highest Environmental Class)*  
**C2** - The transformer is suitable for operation, transport and storage at ambient temperature down to -25°C. Limiting is the mechanical stress on the core steel and coils. Lower temp require special measures of stiffening. Suitable for outdoor installation. *(Highest Climatic Class)*  
**F1** - No special fire hazard is envisaged. Except the characteristics inherent to the design of the transformer, no special measurement are taken to limit flammability. *(Highest Fire Behaviour Class)*  
**N.B.** Transformers capable of operation at -40°C…-50°C are available using special materials.  
**F1** - No special fire hazard is envisaged. Except the characteristics inherent to the design of the transformer, no special measurement are taken to limit flammability. *(Highest Fire Behaviour Class)*  
**N.B.** GEAFOL Transformers are flame retardant and self-extinguishing. 5.5% of transformer material is flammable. |
| Power rating at Ta            | 1000 .. 4000 kVA depending on crane load rating | I DT MC CR calculates the required trafo SN = 1.1 * total RMS power in case of ALM infeeders.  
THD(I) < 2.6% (Total Harmonic Distortion (Current)), THD(V)< 2.3% (Total Harmonic Distortion(Voltage)). *(Approx.)*  
RSC (Relative Short-Circuit power)= 16.44 ≈ 15. A common mode oscillation may occur in the secondary winding with typical frequencies in the range, 50...100kHz on TN-supply. This current will be minimized if an IT-supply is used.  
Heating of outer surface of windings will occur due to skin effect, however hot spots are reduced due to use of aluminium as winding material. |
| Max. permissible ambient temperature Ta | 40 .. 50°C    | Class F (Max. Winding Operation Temp. : 155°C):                                     |
### Vector group

<table>
<thead>
<tr>
<th>2-winding: Dy5</th>
<th>3-winding: Dy5Dd0 – <em>(This Option Recommended)</em></th>
<th>4-winding: Dy5Dy5Dy5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Also Available: Dy5DyN5</td>
<td>2-winding:</td>
<td></td>
</tr>
</tbody>
</table>

- Dy5 is a common vector group in Germany. (Also the standard configuration on Siemens crane systems). Dy11 is common in Europe.
- Dy5Dd0 also possible. Dy5Dd0 with asymmetric power rating is needed if auxiliaries are taken off one of the secondaries. Y-windings in general carry a higher current. Thus D-winding should be used for higher load. If secondary systems are largely similar (e.g. 900kVA and 1100kVA) there is no relevant cost impact. The trafo impedance will not be identical though for both systems.
- **4-winding:**
  - Dy5 or Dy11 require a similar effort. This configuration is useful for the purpose of redundancy.
  - Dy5DyN5 vector group used in case of star connected auxiliary supply in order to have only one transformer on the crane and thus only one M.V. switchgear.

### Secondary voltage (no load)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>For SLM and ALM infeeder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3AC480V</td>
<td></td>
</tr>
</tbody>
</table>

### Tappings

<table>
<thead>
<tr>
<th>Tapping</th>
<th>Electrically on the HV side.</th>
<th>Geographically on the LV side for 3-w. and 4-w. and on the HV side for 2-w.</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/− 5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+/− 2.5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Screen winding between HV/LV

- Not permitted

- The screen winding is undesirable as it increases capacitance between the windings and earth.

### Impedance total

<table>
<thead>
<tr>
<th>Impedance individ. systems</th>
<th>To limit current into ALM infeeder clean power filter circuit.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% in range 4..6%</td>
<td>4-w. trafo has better de-coupling and thus difference total uk vs. individual uk. For secondary coils mounted in closer proximity would allow to reduce core material.</td>
</tr>
</tbody>
</table>

### Max. permissible total DC bias current

- IGBT rectifiers bias the core with DC current, thus the higher the permissible DC bias current, the better. This leads to...
transformer losses due to heating.
4-w. trafo have a long magnetic path allowing higher DC-current bias.

**In general DC bias levels:**
- <0.5% of nominal current have no effect,
- Between 0.5% and 1% cause some problems with noise, heating and harmonics,
- Greater than 1% is to be avoided.

<table>
<thead>
<tr>
<th>Core magnetization</th>
<th>Permissible limit for converter duty trafos: 1.75 Vs/m²</th>
<th>4-w. trafos 2200kVA were sized for 1.725 Vs/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature monitoring winding</td>
<td>1 PTC thermistors for warning, and 1 PTC thermistor for tripping per each L.V. winding. Alternatively (option): PT100</td>
<td>PTC is the most cost-efficient solution. 3RN1022-1DW00 thermistor motor protection tripping units are used in conjunction with PTC’s to allow switching of contactors once resistance of PTC rises.</td>
</tr>
<tr>
<td>Temperature monitoring core</td>
<td>1 PTC thermistor at each leg of the core for tripping.</td>
<td>Present for detection of core saturation in case of ALM failure. Avoid use of PT100 for core due to large number of terminals.</td>
</tr>
<tr>
<td>Insulation class</td>
<td>Class F: max. temp.: 155°C</td>
<td></td>
</tr>
<tr>
<td>Insulation technology</td>
<td>Cast-resin</td>
<td>HV coil resin is cast into metal molds under vacuum.</td>
</tr>
</tbody>
</table>
| Winding type | GEAFOL: Aluminium foil winding comprising axially separated, series-connected individual coils. | Aluminium and cast resin have a similar coefficient of expansion. At 25°C (Room Temperature):
- **Aluminium:** 22.2*10⁻⁶/K
- **Epoxy Cast-Resin:** 35*10⁻⁶/K
At 120°C:
- **Epoxy Cast-Resin:** 70*10⁻⁶/K
Lowest stress from electrical field. |
| Weight | Weight advantage of aluminium windings. |
| Insulation resistance | > 4000 MOhm at 5 kV |
| Insulation test | AC insulation see table BIL per list 1 as standard Option: List 2 |
| Induced voltage test | 2.5 min at 2 x VN (e.g. 900V), 200Hz |
| Partial discharge test | < 5 pC at 2 x VN for 2.5 min |
| No-load losses P0 | ca. 4.6kW for a trafo rated 2200kVA |
| Full load losses for the 3 winding systems at 120°C | |
| LV winding cooling duct treatment | Yes |

See table below **Insulation test carried out between phase & earth.**
Remark: List 1 is not following IEC for switchgear. Isolation level depends on network.

This is better than the requirement stated in the IEC standard.
IEC requires <10pC at 1.3Vn with voltage profile 1.8 VN for 30 sec followed by 1.3 VN for 3 min
Limited by IEC only for distribution trafos (2 different loss categories for given uk) No-load losses are a major factor for the trafo running cost
Within the LV winding coil aluminium (almost pure Al) is exposed.
The aluminium terminals are made of AlSi and are highly resistant against corrosion to prevent corrosion of aluminium parts in salt air.

<table>
<thead>
<tr>
<th>HV connection</th>
<th>Presently Cu busbars.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical termination</td>
<td>Avoid direct contact Cu to Al. Cupal plates are not required if cable shoes are tin-plated.</td>
</tr>
<tr>
<td>Mechanical fixing of core by trapezoidal frame</td>
<td>No (for 2- and 3-winding)</td>
</tr>
<tr>
<td>LV coil wedging system</td>
<td>2-w. and 3-w. trafos: Not required</td>
</tr>
<tr>
<td>Coil support system</td>
<td>For all trafos: Spring clamping instead of standard clamping</td>
</tr>
<tr>
<td>Mounting</td>
<td>Recommended: Bolts &amp; rubber mat (see item &quot;noise&quot; below)</td>
</tr>
<tr>
<td>Noise dampening measures</td>
<td>Machinery house noise level Lwa to be below 85dB.</td>
</tr>
<tr>
<td>Paint</td>
<td>For cranes: core up to 170C: 2-component epoxy paint in azure blue RAL5009 coil in coral red RAL 3016</td>
</tr>
<tr>
<td>Mounting instructions</td>
<td>English and Chinese</td>
</tr>
<tr>
<td>Housing</td>
<td>IP00 (machine builder installs fence)</td>
</tr>
<tr>
<td>Overvoltage protection</td>
<td>None</td>
</tr>
<tr>
<td>Certifications/approval</td>
<td>CSA/UL: The Kirchheim and Brazil factories have no certification, Germanischer Lloyd: possible against extra cost</td>
</tr>
</tbody>
</table>

### Insulation and BIL specification:

<table>
<thead>
<tr>
<th>Rated voltage</th>
<th>AC/kV</th>
<th>BIL list 1</th>
<th>BIL list 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3.6 kV</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>&lt; 7.2 kV</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>&lt; 12 kV</td>
<td>28</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>&lt; 17.5 kV</td>
<td>38</td>
<td>75</td>
<td>95</td>
</tr>
</tbody>
</table>
Sea fastening

1. There should be no requirements for marine environment conditions, apart from the use of specialized paint to counter salty air in order to combat corrosion. Mr. Hofmann could be consulted.