Transformer Maintenance:

Do Transformer Windings need Re-clamping?

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Answer: Possibly ….

Unfortunately, the answer is neither straightforward nor definitive. The answer needs to be considered, case by case, and usually within the context of risk management. This is because re-clamping of transformer windings is regarded as major work and it involves intrusive maintenance. However, transformer major work and transformer maintenance, in general, are very broad topics and beyond the scope of this paper. Publications such as Technical Brochure 445 published by Cigre, provide general guidance on maintenance principles, transformer condition assessments and the decision making processes that lead up to performing major work on power transformers.

This paper explains why windings are clamped in the first place and how a transformer condition assessment should include consideration of the integrity of its coil clamping. The paper discusses the various tests and checks that are used to assess the integrity of coil clamping. Then, two case studies are provided to show how coil clamping can be surveyed, and how it was shown that the integrity of the winding clamping was compromised, and demonstrates how re-clamping the windings can be implemented as a corrective action.

Why Windings are Clamped in the First Place

The function and importance of clamping the transformer windings needs to be understood. Coil clamping is an important facet of transformer design. Applying the correct coil clamping pressure allows for:

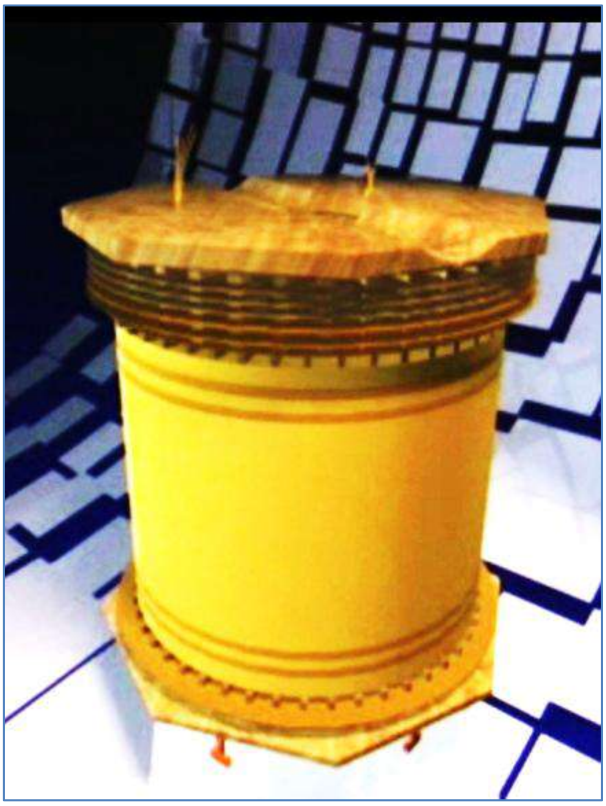
(i) the complete internal assembly (core and coils) to be lifted by a crane,
(ii) the bracing of the transformer windings during transportation,
(iii) the reduction of the operating 'load noise' level of the windings and
(iv) most importantly, assists the transformer to survive short-circuit faults.

Power transformers of core-form construction have their windings arranged coaxially around each wound limb of the core assembly. The windings are nested together to form robust cylindrical phase assemblies to achieve close magnetic coupling of the windings and a very high space factor for the winding conductors. The phase assemblies are clamped with axial pressure applied across their upper and lower pressure rings. The magnitude of that clamping force is normally commensurate with the magnitude of the axial force exerted by the windings during short-circuit faults on the transformer. In effect, the clamping force is a preset reaction force and, as long as it exceeds the short-circuit force, the windings will remain in compression and therefore be less likely to dislocate or be disturbed.

During manufacture, individual windings are wound on a winding machine. Each winding is necessarily made over length because the paper covered conductor and insulation spacers initially have a high moisture content (6 to 12%). It is not until the winding is clamped in a jig and dried in an oven that the winding length becomes correctly sized and stabilized. For optimal results, the drying must be performed under spring pressure (typically between 3 and $10N/mm^2$). A combination of shrinkage and plastic deformation reduces the paper build by about 10% and the pre-compressed transformerboard spacers and blocks by about 5%.

(1) (2)

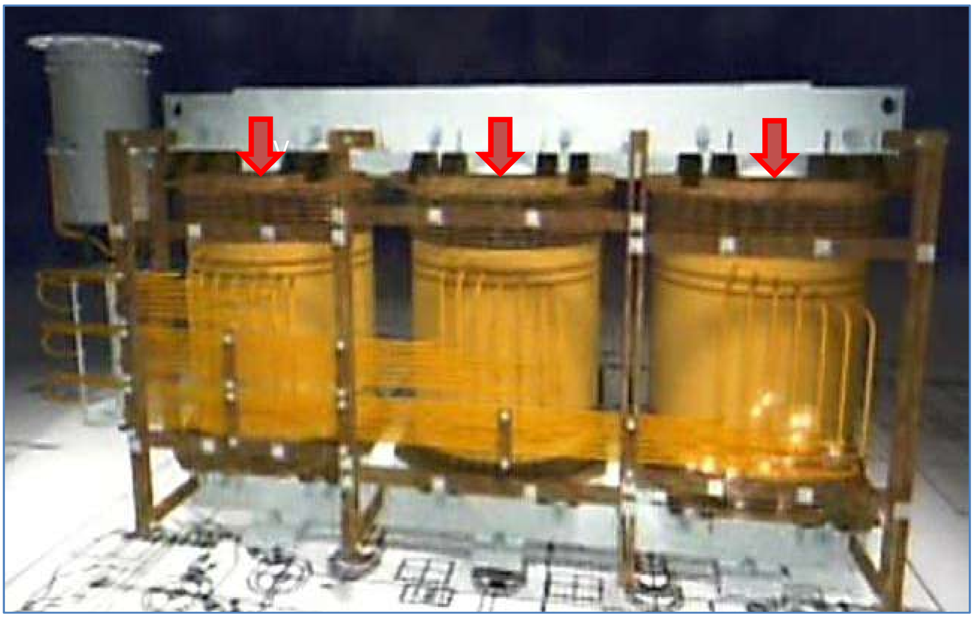
The pre-sized windings can then be nested together (1) to form a complete phase assembly (2), and this ensures that the winding groups align correctly in axial position. If necessary, the winding lengths can also be adjusted slightly during phase assembly to perfect the alignment. The completed phase assemblies are then kept under compression by clamping the top and bottom pressure rings (3).



(3)

Maintaining the axial length of the phase assemblies is very important. If the assemblies are over length, then the top yoke and yoke clamps cannot be fitted to the core limbs. The internal assembly is completed by blading up the top yoke laminations and locking the top yoke clamps with the lower core frame. At this stage, the overall coil clamping force is applied and is *intended* to be set for the life of the transformer. However, a final adjustment of the coil clamping may still be required due to the shrinkage (relaxation) that occurs with oil impregnation. Furthermore, the modern transformer typically does not have adjustable coil clamping screws, as were sometimes used in the past. Instead, the top yoke clamps bear directly down on the top pressure rings of each phase assembly (4), and they usually employ pressure pads, brackets and blocks of insulation to evenly distribute the clamping force over and around the coil circle.

(4)



Importance of Coil Clamping for the Short Circuit Withstand of a Transformer

During a short-circuit fault on a transformer, the windings are effectively in unstable equilibrium. The coil clamping helps to maintain a near equilibrium (or minima of the short-circuit forces). Retaining the relative position of the windings, stabilizing their length and maintaining the residual clamping force is very important for short-circuit withstand of the transformer. Under a short-circuit fault, the windings repel and exert large axial and radial forces that effectively try to separate the windings. The size of the coil clamping force is designed to be commensurate with the expected magnitude of axial forces exerted during the short-circuit event. This keeps the windings in compression and therefore stable. However, any alteration to a winding's axial length or its relative axial position through dislocation or collapse of the winding conductors is likely to loosen the coil clamping. Furthermore, these changes also alter the winding ampere-turn distribution. Any change in the relative position of the ampere-turns will alter their fine positional balance and symmetry (between the winding groups) and that invariably results in substantial increases in the short-circuit forces. For these reasons, short-circuit withstand capability of a transformer is dependent on the status of its coil clamping and therefore coil clamping should not be compromised.

What Constitutes a Compromise of the Coil Clamping?

Essentially, the coil clamping will be compromised if the residual clamping pressure has relaxed enough to then allow dislocation or mechanical deformation of the winding during a short-circuit fault. Coil clamping may also be compromised either by the effects of repetitive short-circuit faults or a single protracted short-circuit fault. This can be due to the cumulative plastic deformation of the axial insulation components, or to a partial winding collapse or to conductor tilting. However, the most common way that the coil clamping relaxes is with shrinkage of transformer cellulosic insulation through ageing.

During transformer service, the insulation shrinks with the onset of advanced paper ageing. This is because cellulose loses substance. As cellulose ages, it is being converted into CO_2, CO, water and furans. Furthermore, the cellulose polymer chains undergo scission to form shorter chain molecules with reduced polymerisation of their cellulose fibres. As a direct consequence, paper shrinkage allows gradual relaxation of the residual clamping pressure. Despite some limited elasticity or recovery to expand again, the structures can still become loose. This can occur either during the vigorous oscillations of a short-circuit fault or by eventually vibrating out after clamping pressure is lost. Not all of the insulation structure is necessarily keyed, glued, tied or dowelled to prevent this dislocation. Furthermore, repetitive short-circuit events can cause cumulative bruising and dislocation of components in the insulation structure. Should an axial or radial spacer or support block be displaced due to these cumulative effects, or whether it simply vibrates loose (having lost its clamping pressure) then the void this creates provides room for winding dislocation during short-circuit events resulting in even greater short-circuit forces to be exerted and further winding damage.

In the last fifty years, significant changes in winding design, insulation structures and insulation materials have tended to allow heavier clamping pressures to be used when completing winding phase assembly. This was largely brought about by the introduction of pre-compressed transformerboard in the 1950s. The use of heavier clamping pressure reduces the likelihood that winding compression will be lost completely during normal service life.

Previously, transformer manufacture used lower density insulation materials such as ‘Elephanthide’ blocks and boards, presspaper, soft paper angle rings, or petalled collars, in the end insulation structure of the phase assemblies (above and below the winding ends). These materials are relatively spongy by nature and could only be lightly clamped compared to modern standards using pre-compressed transformerboard. As a result many transformers from that era now exhibit loose coil clamping. These softer materials prove to be quite challenging to stabilize. Correct sizing of the axial lengths of the winding groups is challenging too. Their coil clamping arrangements typically have pressure screws to make large tolerance adjustments possible.

The Limitations for Electrical Tests to Discern Loose Coil Clamping

Electrical tests such as single phase leakage reactance and inter-winding capacitance are only sensitive to major changes in the dimensions or spacing of the winding geometry and are typically only able to discern major disturbance or damage to the windings where winding lengths or radial spacing change by at least a few percent. The relaxation of coil clamping or the shrinkage of winding insulation, in itself, does not sufficiently alter the winding geometry to detect change. Frequency response analysis (FRA) is more sensitive to localized winding dislocations or movement, but FRA too is unlikely to actually discern relaxation of coil clamping. Instead, these electrical tests are primarily used to detect winding damage caused by short-circuit faults. Accordingly, the only reliable way to evaluate the integrity of the coil clamping is to perform an internal inspection and to check the residual clamping pressure.

Methods used to Survey Residual Clamping Pressure

An inspection of the internal assembly makes the following survey possible:

(i) Alignment of the phase assembly heights
(ii) Measurement of phase assembly height to a common datum
(iii) Checks for spacers, blocks and packing shims fallen out of position
(iv) Checks of alignment of spacers, block and shims
(v) Observation of relative winding movement or distortion of shape
(vi) Hand looseness of coil clamping devices
(vii) Hand looseness of any block work in the end insulation structure
(viii) Tonal differences when accessible block work is lightly tapped
(ix) Ease to dislocate accessible block work when again lightly tapped
(x) Measurement of residual clamping pressure (where this is practicable)

However, the extent of the coil clamping survey performed on a particular transformer may be limited by the available ‘hands-on’ access to the internal assembly. Access may be restricted by having only a few access covers, or by the limited reach of confined space access or the ability to remove the transformer’s bell cover or lid. For these reasons, such surveys are usually performed as a part of other major work on a transformer. Note that the required skills, resources and expertise increases in complexity down this list.

How to Measure the Residual Clamping Pressure

The measurement of residual clamping pressure is not always practicable. However, any coil clamping arrangement that is adjustable, inherently had to have some way of measuring the force, effort, torque or applied pressure that was originally used to set it. There are two common methods.

Torque Wrench Method
A common practice for pressure screw arrangements is to the record the torque wrench loading at each pressure screw position and tabulate (or map) the load distribution on all the phase assemblies and compare them. Note that it is usual to measure the torque required to infinitesimally increase the existing load at each pressure screw (rather than the torque required to release it). The disadvantage with this method is that any adjustment at one single point may slightly influence the loading at the other pressure screw positions around the coil circle.

Hydraulic Jack Method
A preferred and almost universal method to measure residual clamping pressure is to use four hydraulic jacks (cylinders) to bear evenly down on the top pressure ring of the phase assembly. The main limitations are whether there is enough room to position the jacks and whether suitable pressure points can be found to extend each jack between the top yoke clamp and the winding pressure ring. By gradually and equally increasing hydraulic pressure on the four jacks, it is possible to record, one by one, how much force is required to overtake the existing clamping force at each clamping point. Hydraulic cylinders provide ease of applying force and a suitably slow rate of increasing the force. They also provide a means of quick release of force, if required for safety. Positioning the four hydraulic cylinders approximately 90º apart around the coil circle ensures that the application of force is simultaneous and evenly distributed around the coil circle

Typically, the equipment required includes (i) four hydraulic cylinders (10 or 20 tonne capacity) with a known piston surface area, (ii) one 5-way manifold with isolation valves for each of the four cylinders, (iii) one hydraulic pressure gauge and (iv) a hand operated hydraulic pump (with an in-line isolation valve to lock the applied pressure). The photographs below show examples of this equipment. Note that a confined space access permit was required to position these cylinders.

The following case studies illustrate how each element of the coil clamping survey listed above may be performed and how deficiencies, if found, may be corrected.

Case Study 1: Three 110/11kV 50MVA Generator Step-Up Transformers of the Same Design (two manufactured in 1968 and one in 1970)

Access to the coil clamping on these units was facilitated by removing the bell cover (5).

(5)

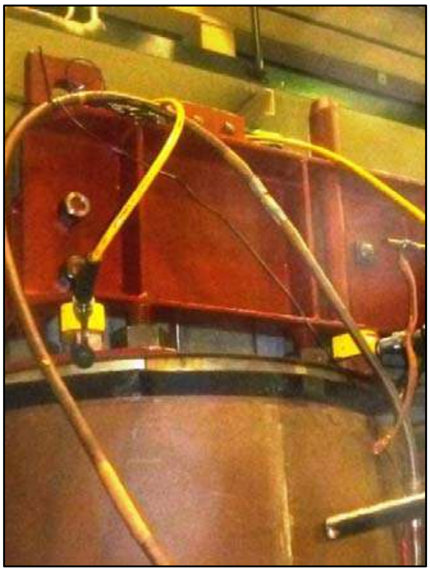
(6)

Photograph (6) shows how sighting horizontally across the three pressure rings at the top of the phase assemblies was used to assess the alignment. The residual clamping pressure was then surveyed using hydraulic jacks. An important safeguard for this procedure is the calculation of the maximum permissible hydraulic pressure. This is so that an excessive clamping force does not occur. These calculations should always be performed by an experienced transformer design engineer. The calculated clamping forces used for these transformers are shown below. The permissible clamping pressure on the spacers within the windings is the determinant. This transformer design is relatively simple having only two radial winding groups, the LV and the HV.

Calculation of Maximum Clamping Force on each Phase Assembly

	Radial Depth	**Spacers /circle and width**	**Compressed Area**	**Max Clamp Pressure**	**Clamping Force**
LV	**55mm**	**16 x 35mm**	**30800mm^2**	**2.76N/mm^2**	**8.67t**
HV	**64mm**	**20 x 35mm**	**44800mm^2**	**2.76N/mm^2**	**12.62t**
MAXIMUM CLAMPING FORCE REQUIRED					**21.29t**

The hydraulic jacks that were used each have an effective piston area of 14.5cm^2. Using a pump hydraulic pressure of 169 bar on four jacks will exert a total force of 10t. Accordingly, the maximum hydraulic pressure using four hydraulic jacks will be 360 bar if the 21.29t is not to be exceeded. The hydraulic jacks were positioned around each phase assembly as shown below (7) and (8).



(7)

(8)

The residual clamping pressure (expressed as hydraulic pressure) on the three transformers are tabulated below and illustrate survey outcomes for three transformers of identical design.

Hydraulic pressure (bar) required to	Transformer 1			Transformer 2			Transformer 3		
	A	B	C	A	B	C	A	B	C
Loosen **first** screw	60	hand loose	60	10	30	10	50	50	50
Loosen **all 8** screws	110	170	>280	90	110	100	100	100	100

The table above shows the variation of residual clamping pressure between the three phase assemblies (A, B and C) on any one transformer, as well as that between the transformers. The hydraulic pressure was not allowed to exceed 280 bar to respect the aged insulation observed in these transformers. The degree of polymerisation value for a paper sample from Transformer 1 was very low at 325. Clearly, all three transformers have lost their original clamping pressure to various degrees.

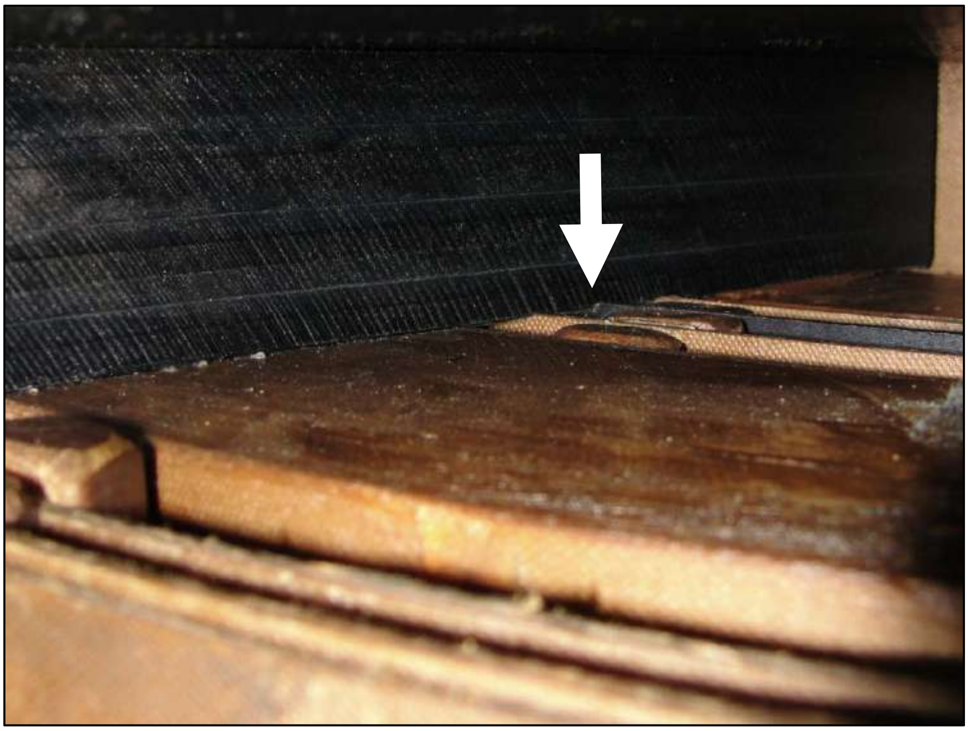
Re-clamping the Windings

An important observation to be made from any clamping survey is the value of the maximum pressure required to release the last pressure point. That value becomes the minimum target value for re-clamping all three phases.

However, having set a target value is not necessarily the only factor, or risk, to be considered. The re-clamping on Transformers 1 and 2 had to be curtailed when it was observed that some insulation parts were on the verge of interference crushing. The table below shows the final pressure settings on each phase assembly.

Hydraulic pressure (bar) required to set final coil clamping	Transformer 1			Transformer 2			Transformer 3		
	A	B	C	A	B	C	A	B	C
	210*	190*	270	270	185*	190*	300	300	300

A target clamping pressure of 270 bar was selected for Transformers 1 and 2 to respect the low DP values of their paper samples. A higher target clamping pressure of 300 bar was selected for Transformer 3 because its minimum DP was much higher at 615. The original factory pressure is expected to have been 360 bar. An asterisk denotes which phase assemblies had to curtail reclamping at lower pressure settings because some insulation was on the verge of crush damage (9).

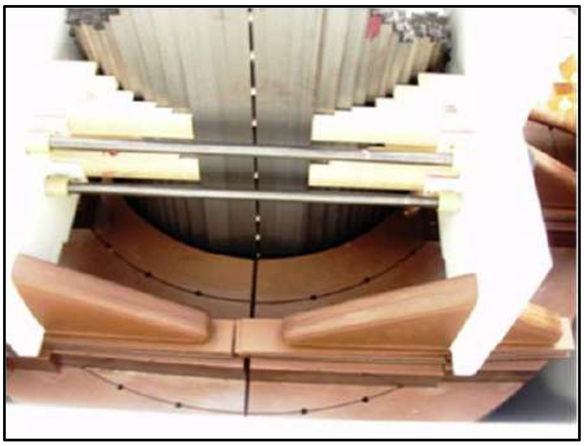


(9)

Case Study 2: 220/11kV 75MVA Generator Step-Up Transformer (manufactured in 1997)

Access to the coil clamping on this unit was facilitated by removing its welded lid (10). Note the upper pressure rings were made in two pieces (11) and so is not as strong as a one piece ring.

(10)



(11)

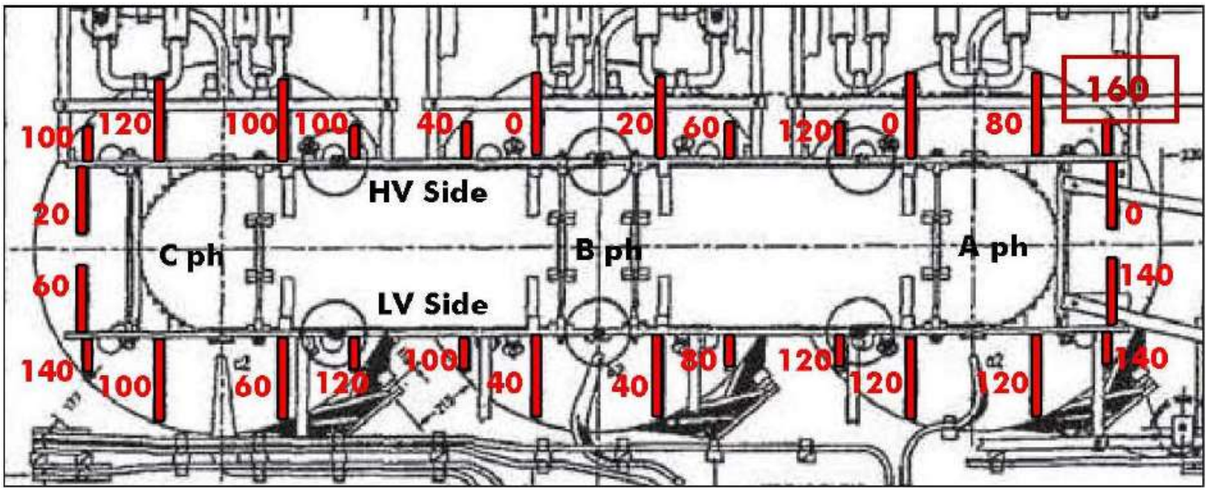
Photograph (12) shows how the windings are clamped by a set of triangular brackets attached to the top yoke clamps. The brackets each bear down on a stack of blocks and the pressure ring. Final adjustment to the clamping is made by adding (or removing) thin shims of insulation at the top of each stack of blocks.

(12)

(13)

The clamping on 'B' phase was found to be loose (13). The group of shims and thin block shown above was so loose that it could be pulled out by hand. During a short-circuit fault, the loose shims would be likely to vibrate out of position and allow winding dislocation. Other blocks and shims could be dislocated by tapping lightly with a hammer. This finding shows that even modern transformers are susceptible to relaxation of coil clamping. The lowest DP value for a paper sample from this transformer was 503.

This survey diagram (14) utilises a plan view of the internal assembly with the coil clamping bracket positions highlighted in red. The usefulness of a diagram like this is to indicate the hydraulic pressures (in bar) required to release each bracket in turn. Notice on ‘A’ phase that the bracket exerting the heaviest clamping pressure is back to back with a bracket that has shims that are hand loose. This clamping arrangement has serious deficiencies.



(14)

Four hydraulic jacks were arranged around each coil circle and hydraulic pressure increased in 20 bar increments to record this survey. The packing shims were hand loose under three brackets (before applying any pressure). The maximum hydraulic pressure required to release clamping was 160 bar on ‘A’ phase and this pressure is less than half the expected factory setting (404 bar) on each phase assembly. A conservative target pressure of 200 bar was then used to re-clamp each phase assembly with the knowledge that at least 160 bar was permissible. Cable ties were then added to capture the shims (15).

(15)