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TECHNICAL BROCHURE

Power transformers and reactors

**On-Site Assembly, On-Site
Rebuild, and On-Site High Voltage
Testing of Power Transformers**

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On-Site Assembly, On-Site Rebuild, and On-Site High Voltage Testing of Power Transformers

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Executive summary

The aim of the working group was to address the new challenges presented by on-site assembly, on-site rebuild, and on-site high voltage testing.

The scope of the working group was:

1. Survey of international experience and best practice with on-site assembly, on-site rebuild, and on-site high voltage testing.
2. Applications and case studies for on-site assembly including alternatives such as 2x3-phase transformers in parallel or 3x1-ph transformers to reduce mass and dimensions.
3. Design and construction issues, mainly for on-site assembly.
4. Dis-assembly and re-assembly issues, mainly for on-site assembly but also on-site rebuild.
5. Scope of works test etc., mainly for site-assembly.
6. Applications and case studies for on-site high voltage testing including limits of what is possible with currently available technology.
7. Any additional requirements for pre-commissioning and trial operation.

Site Assembly of large transformers was shown to be a viable solution for severe transport limitations. Some countries (Japan in particular) have severe weight or size limitations for transport that make it near impossible to ship a transformer with desired high MVA rating. Solutions have been developed that allow the transformer to be manufactured and then the windings and core dismantled to be shipped to site in several transportable segments for full assembly on site. A temporary building on site with a controlled environment is required for the assembly since windings and cellulose are exposed. Fixed cranes in site buildings or mobile cranes are used for the lifting. On-site testing may be done after the site assembly.

A survey of site assemblies performed by several manufacturers in Japan, Europe and China showed the below solutions:

- A 3 phase 5 limb core design was shown to be typically utilized. The core is manufactured in 4 separate “U” cores that can be easily combined at site. The windings are nested together as a single phase for transport to site. At site the “U” cores are assembled on to a bell type tank base and the winding phases are landed onto the core main limbs. The transformer is fully assembled and tested in the factory before being dismantled and shipped to site.
- A 3 phase 5 limb core design was shown also where the core legs and yokes are shipped individually to site. A core stacking table is required at site where the bottom yokes are inserted. The core is up-righted and then the winding phases are installed. The top yokes are inserted, and the active part is installed.
- Solutions with shell form type transformers were shown
- A variant of the site assembly was shown to be the split tank type transformer. The transformer is divided into several tank components that are connected on site such that it will be an equivalent three phase or single phase required rating. For this type, the windings and cores are not assembled on site.
- These solutions have been done on hundreds of transformers globally and ratings above 1 500 MVA have been achieved. The field failure rate was shown to be very low.

A survey was similarly done for on-site rebuild of existing transformers requiring new windings. In the event of failure, it may not be possible or practical to transport a transformer to a factory for repair. This may occur if railway lines or bridges have been decommissioned and the existing transformer can no longer be shipped out of the site in the same way it arrived. It is possible to disassemble the transformer and active part on site, and repair or replace damaged windings. This is termed “site repair” and involves many similar challenges and solutions as the above discussed on-site assembly. The survey included site repairs done in Canada, China, Japan and Europe.

The solutions for the site building / clean house were shown which are special purpose buildings that are reused and contain the necessary lifting systems or have removable roof panels for mobile cranes. It may be possible to use an existing building at site (i.e. generator hall with high bay ceiling and overhead crane) or a local company can prepare a tent type building on site. The site building must have a controlled atmosphere for low humidity and minimization of dust.

A survey was done for the dryout of the core & windings. The windings are manufactured in a transformer factory and dried out by vapor phase method prior to shipment. The various methods to limit moisture ingress during the site assembly process were shown. The final dryout was shown to

be done by either hot oil / vacuum cycles, Low Frequency Heating (LFH) method or by site vapor phase.

The final testing of the assembled transformer at site varied in the survey. Some manufacturers test the assembled transformer in the factory (and some only as design tests on the first transformer) and then only perform low voltage tests at site. Other manufacturers only do full testing at site on the assembled transformer (no factory testing). All situations were proven to be successful with low field failure rates.

Technology developed for mobile test equipment was shown that allows all parameter and dielectric verification tests to be performed at site. Loss measurement, impedance measurement, temperature rise, applied voltage and induced voltage are performed using AC HV test equipment. Lightning impulse voltage and switching surge voltage tests are performed with a mobile HV impulse test set. DC tests such as DC applied voltage or DC induced voltage tests are performed with mobile DC test equipment.

Modern mobile AC HV test systems utilize an Electronic Power System (EPS) which can widely vary the output voltage and output frequency. The system includes inductive and capacitive compensation and a step-up-transformer that can be switched manually into many different configurations. By using external capacitor banks, a temperature-rise test can be also performed at site with this system. Transformers up to 800 kV have been tested with this type of mobile AC HV test system for induced voltage, applied voltage and loss measurement. Temperature-rise testing is limited by available capacitors and power supply (typically a very large 2 MW diesel generator).

The HV mobile impulse test set is a modified version of factory impulse test equipment where the test circuit lays down flat into a 40 ft. ISO container or road trailer for shipment. Mobile impulse sets that can perform testing up to 1800 kV BIL are in use and higher voltages are technically possible.

The methods and quality controls were surveyed by several manufacturers. Detailed quality checks, testing, clean house requirements, processing / dryout and inspections are shown.

It was overall demonstrated that varying solutions have been developed and successfully executed for site assembly and site repair for more than 20 years. The increased risks of performing tasks at site such as installing windings, core assembly, active part dryout and dielectric testing have all been managed. The site assembly and site repair are shown to be a viable and fully possible solution and are done in accordance with a local regulations, practices, and specifications.

This technical survey of on-site assembly and on-site rebuild is new for power transformers. This technical brochure shows a collection of many different procedures and experiences of the on-site assembly and the on-site rebuild. Many experiences of the on-site assembly show reliability with only FAT (Factory Acceptance Tests) and on-site acceptance tests without on-site high voltage testing (Japan in particular). This technical brochure summarizes the quality assurance aspects to ensure high reliability under on-site work..

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1. Introduction

1.1 Background

Most large power transformers are transported to site with the active part fully assembled inside the tank. Installation work at site is limited to assembly of external parts and filling with oil or other dielectric fluid. The mass of the main tank including the active part may be very high for large power transformers (more than 200 t).



Figure 1.1 - Severe transportation condition (see CIGRE TB 673 page 4) ^[1]

To transport the main tank with active part using existing infrastructure may not be possible for all sites. For such sites, a new technology has been developed to allow installation of large power transformers without the need to develop new infrastructure. The active part of the transformer is prefabricated in large sections for assembly at site. This greatly reduces the maximum transport mass but introduces new challenges during the assembly process at site. It is applicable mainly to transformers rated at 150 MVA and larger and 145 kV class and higher.

A similar situation may arise for existing transformers at some sites. In the event of failure, it may not be possible or practical to return the transformer to a factory for repair. However, it may be possible to disassemble the transformer on site, including the active part, and repair or replace damaged components. This involves many similar challenges as with on-site assembly.

Following on-site assembly or on-site rebuild, and sometimes also in other circumstances, there is a need to prove that the transformer is in good condition and ready for service. For transformers which are not assembled or rebuilt on site, this is normally done by high voltage testing in a factory test laboratory. For transformers which have been assembled or rebuilt at site, there may be still a need to make high voltage tests, usually using mobile equipment. This introduces additional new challenges.

On-site assembly and on-site rebuild cases are surveyed in this document. This technical brochure shows a collection of many different procedures and experiences of the on-site assembly and the on-site rebuild. Many experiences of the on-site assembly show excellent reliability with only FAT and without on-site high voltage testing (Japan in particular). This technical brochure summarizes the sequences of quality assurance to ensure high reliability under on-site work.

1.2 Aim and Scope

The aim of the working group was to address the new challenges presented by on-site assembly, on-site rebuild, and on-site high voltage testing. This brochure presents many cases from around the world to introduce state-of-the-art techniques and demonstrate what possibilities exist today. The described cases demonstrate differences in procedures somewhat due to varying local rules and regulations.

Scope

1. Survey of international experience and best practice with on-site assembly, on-site rebuild, and

on-site high voltage testing.

2. Applications and case studies for on-site assembly including alternatives such as 2x3-phase transformers in parallel or 3x1-ph transformers to reduce mass and dimensions.
3. Design and construction issues, mainly for on-site assembly.
4. Dis-assembly and re-assembly issues, mainly for on-site assembly but also on-site rebuild.
5. Scope of works test etc., mainly for site-assembly.
6. Applications and case studies for on-site high voltage testing including limits of what is possible with currently available technology
7. Any additional requirements for pre-commissioning and trial operation.

1.3 Definitions

1.3.1 On-site assembly

To assemble a transformer at the installation site including assembly of the windings, and complete or partial assembly of core.

1.3.2 On-site rebuild

To rebuild, repair or refurbish of a transformer at the installation site including complete or partial replacement of windings.

1.3.3 On-site high voltage testing

To test of a transformer at site with high voltages for dielectric tests at specified or reduced voltages.

1.3.4 Split-tank type transformer

To construct a transformer where the main components are split between several different tanks, so that when installed it will have equivalent performance to a conventional transformer with the same rated power and voltage.

2. Survey of On-Site Assembly

2.1 Experiences in Japan

2.1.1 Introduction

This chapter gives an overview of the historical background and developments of the on-site assembly transformer technology in Japan following changes to transport infrastructure and increases in transformer ratings, size and mass. This is illustrated in Figure 2.1.

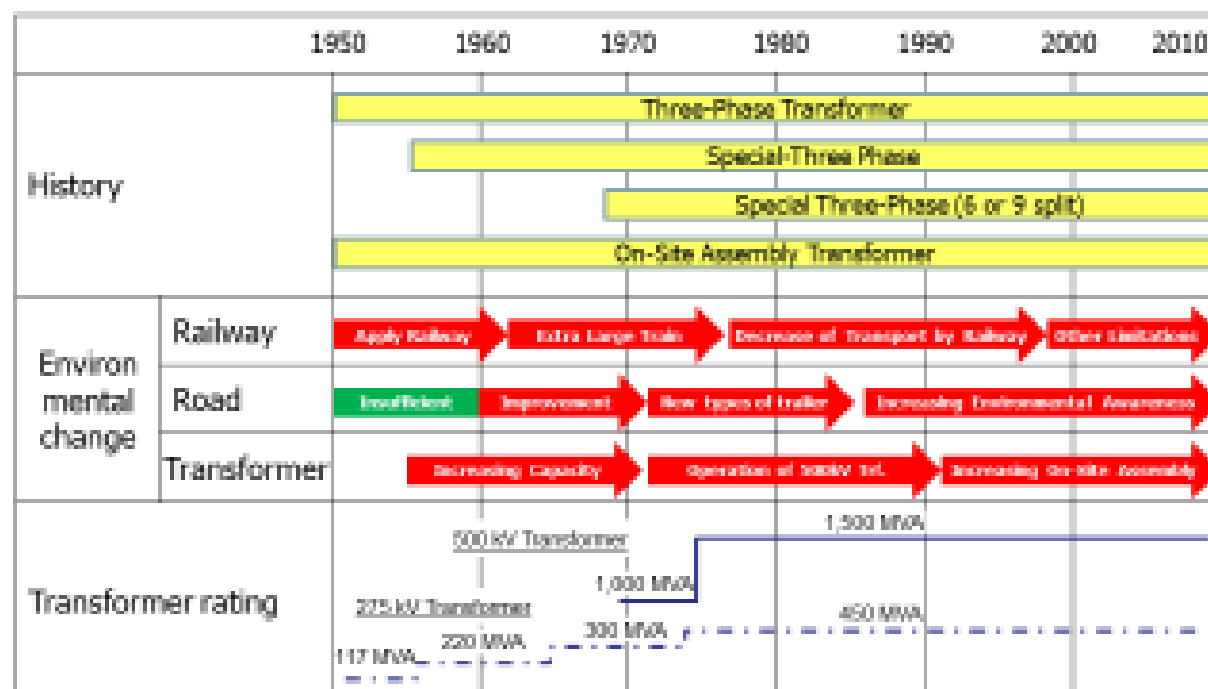


Figure 2.1 - Development of On-Site Assembly Transformers in Japan

In the post Second World War revival, high-voltage large-capacity power plants and substations were built. The transportation of large-capacity power transformer became a critical issue due to insufficient transportation infrastructure and remote mountainous locations of hydroelectric power plants.

The application of special three phase transformers in the 1950's was developed to reduce transportation size. At this time, the on-site assembly of transformers was also developed. After passing factory acceptance tests, the transformers were disassembled to be suitable for the transportation limitations and re-assembled on-site.

There was a brief decline in the application of on-site assembly due to improved road infrastructure and the development of large-scale special trailers for transportation such as the Schnabel type trailer.

In the 1980's, changing environmental conditions and changing regulations on road/railway transportation led to very severe transport restrictions. As a result, transportation costs increased significantly. New types of on-site assembly transformers were developed and applied from the viewpoint of minimum total cost and reduced transformer size and installation footprint [2].

Presently in Japan, the on-site assembly transformer has become standard for large-capacity 500 kV transformers. Three Japanese experiences are surveyed.

2.1.2 Experience A with Core Type

2.1.2.1 Application trend of on-site assembling of transformers

In the last 20 years, the application of on-site assembly of transformers has increased dramatically. Figures 2.2 and 2.3 show the production record of on-site assembly of transformers by one company (within Japan and China) since 1992. There are several reasons for the increase in application: on-site assembly of transformers can provide the same quality as factory assembled transformers, integral 3-phase construction is now possible for 500 kV transformers, cost reductions in on-site assembly of transformers, and lastly transportation restrictions have become harsher. Furthermore, there are advantages from the energy management perspective by reducing the environmental impact, de-bottlenecking the transportation constraint, responding to accident and replacement requirements, reducing system losses and improving life cycle cost (LCC).

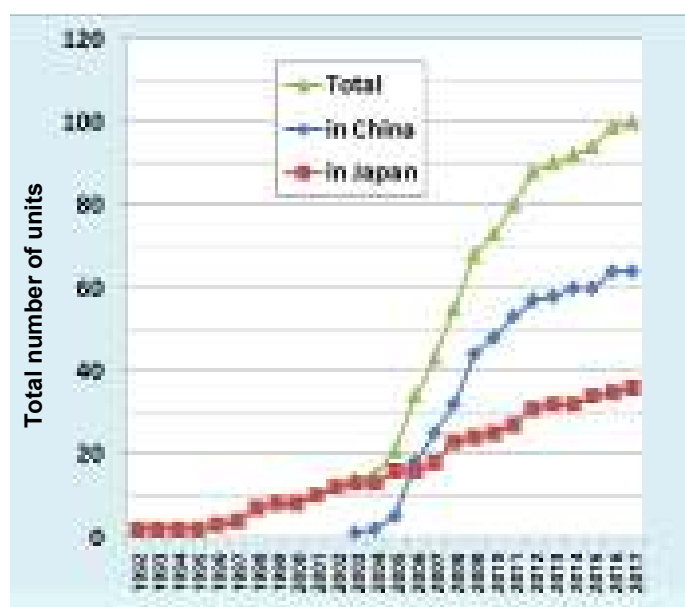


Figure 2.2 - Production record of on-site assembly transformer (in China and Japan)

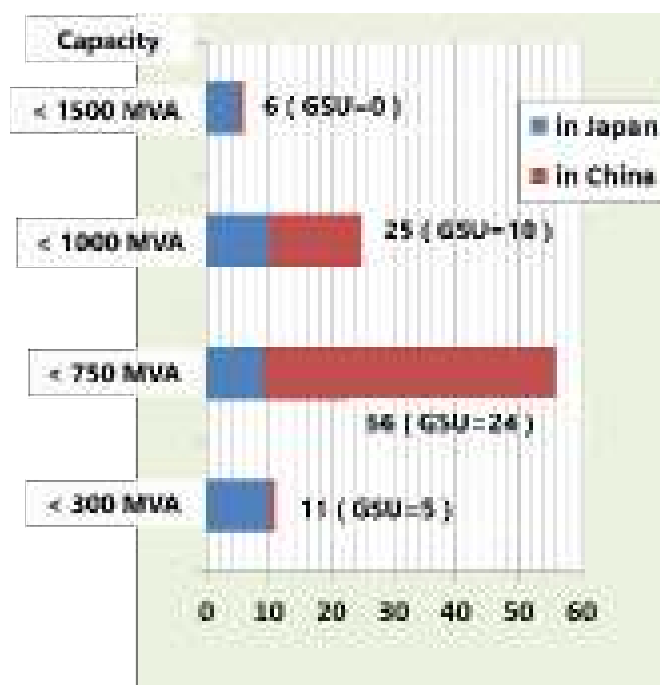


Figure 2.3 - Number and Capacity of on-site assembly transformers

2.1.2.2 Construction and effect of application

(1) Concerned items for construction

Disassembly in the factory is minimized as much as possible and on site quality control is kept simple but yet duplicates the verification done at the time of factory assembly.

(2) Construction features

- a) Core Construction - 3-phase 5-leg core is applied to on-site assembly transformers. By configuring it to disassemble only the upper yoke, the time for the on-site assembly is substantially reduced. The lower yoke is configured to be segmented into 4 pieces of U shape taking advantage of the standard core structure of a 3-phase 5-leg main core which allows it to be separated at the centre part (Figure 2.4 (a)). By using this construction, it is possible to assemble the core on-site in 4 days (erection of U shape unit x 2 days, upper yoke assembly x 2 days).
- b) Winding Construction - The winding is assembled as a unit (nested per phase) and clamped with the upper and lower press rings. The nested winding phase can be handled as a single unit, minimizing the time for assembly of the winding on-site. To prevent moisture absorption and dust-proof during the transportation and on-site assembly, the winding unit is packed with the polymer film (Figure 2.4 (b)).
- c) Tank Construction - The tanks are horizontally split. The core & coils are assembled on to the lower tank. The number of segments used for the upper tank construction is decided in accordance with the transportation condition and the transport trailer to be used. After the assembly is completed, the outer circumference flange part is welded to be integral construction.

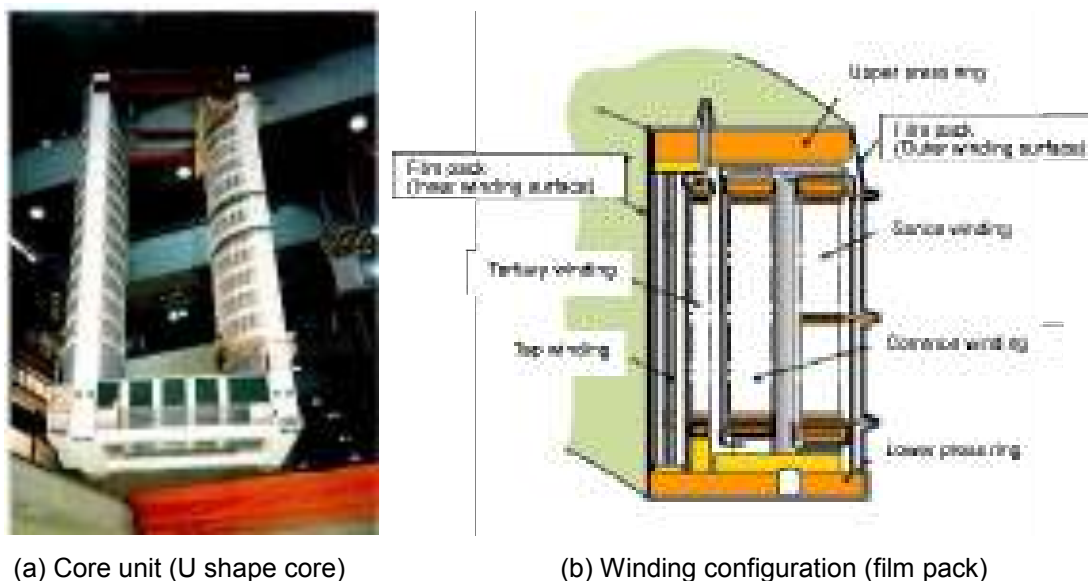


Figure 2.4 - Core unit and Winding configuration

- d) Transportation Construction - The core U shape unit and winding unit are mounted and fixed on a dedicated transport tank for transportation by a low platform trailer. The standard transportation control criterion (maximum acceleration < 3G) was developed by performing an actual transport test up to 5G using a vibration generator (since the transportation mode is different from conventional transformers).

(3) Effect of application - By applying on-site assembly transformers, other advantages were realized:

- a) Reduction of Transportation Cost and Lead Time - Transport costs such as reinforcing roads and bridges for heavy loads are no longer required. Vehicle costs are reduced as no special freight cars or trailers are used.
- b) By changing from the configuration from 3 units of single-phase to a normal 3-phase unit, the volume of materials required for the transformer production is reduced and additionally, the site layout footprint is decreased (Table 2.1).
- c) Realizing a Lower Life Cycle Cost Transformer due to Increased Design Flexibility - By reducing the volume of required materials, the equipment is optimized by means of life cycle cost assessment and impact on the environment.

It is expected that transportation constraints will become more severe. On-site assembly will be the

principle technology to support the current and future electrical power infrastructure system for failures of existing equipment and replacements of deteriorated equipment.

2.1.2.3 On-site assembly procedure

(1) Quality Assurance

The quality goal of on-site assembly is to reproduce the transformer at site after factory disassembly of the active part. The process of the re-assembly is shown in Table 2.2.

Quality control standards for the on-site assembly are:

1. Apply the same control standard as that of the factory assembly.
2. Perform quality checks with intermediate electrical tests.
3. The on-site assembly environment should be similar to the factory with dust-proof management (dust-proof volume 20 cpm or less) and moisture-proof management (relative humidity 50 % or less).

Items of the quality control standards for each process are shown in Table 2.3.

Table 2.1 - On-site assembly transformer comparison (500 kV – 1 500 MVA)

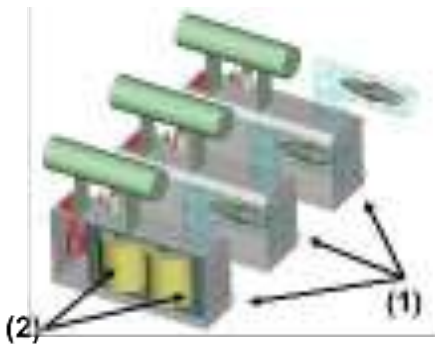
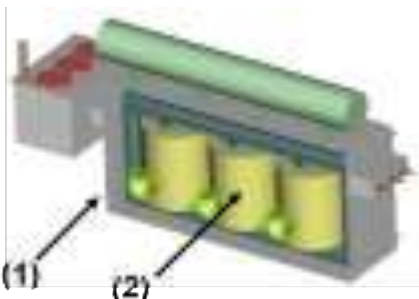
type	Single phase transformer	On-Site assembly transformer
Drawing		
Configuration	(1) 1phase-500 MVA transformer X 3 (2) Two winding-groups / 1 phase	(1) 3phase-1 500 MVA transformer X 1 (2) One winding group / 1 phase
Mass	Total mass:100 %	Total mass: 75 %
Area	Installation area: 100 %	Installation area: less than 50 %

Table 2.2 - Basic assembly process of on-site assembly transformer

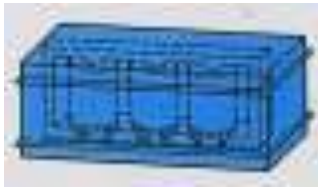
1. Core setting	2. Coil insert and upper yoke assembly	3. Tank and internal lead assembly
		
Following can be eliminated: >Leg stacking >Lower yoke assembly >Core erection	Following can be eliminated: >Drying process at site Dust /moisture will be controlled.	Lead connection and tank assembly

Table 2.3 - Quality control items for on-site assembly transformer

Items		Workflow	Inspection items
Disassembly at factory		1. Oil drain 2. Replacement with dry air 3. External parts disassembly 4. Tank decomposition 5. Internal activity lifting 6. Internal lead disassembly 7. Upper parts, upper yoke disassembly 8. Windings lifting 9. Film packing of windings 10. Lower parts of core disassembly 11. Core disassembly (U-shape core)	-- -- 3. Packing, inspection before shipment 4. Packing, inspection after shipment -- 6. Packing, inspection before shipment 7. Packing, inspection before shipment -- 9. Packing, inspection before shipment 10. Packing, inspection before shipment 11. Packing, inspection before shipment
Transportation		Transport from factory to site	--
Assembly at site	Work in the clean house	1. Clean house assembly 2. Bottom tank on-base 3. Core re-assembly (U-shape core) 4. Suspended the windings and insert 5. Core re-assembly (upper yoke) 6. Internal leads re-assembly 7. Tank re-assembly 8. Tests of active part 9. Clean house disassembly	-- 2. Site acceptance inspection 3. Site acceptance inspection 4. Site acceptance inspection 5. Site acceptance inspection 6. Site acceptance inspection 7. Site acceptance inspection -- --
	External assembly & oil filling	10. External parts assembly 11. Bushing lead connection 12. Vacuum, oil filling and circulation 13. Repair painting 14. Test of finish product	10. Site acceptance inspection 11. Site acceptance inspection -- -- --

(2) On-site assembly work procedure (Phase1) (1992~2007)

- (i) Transportation Unit - For transformers completed with tests at the factory, its internal assembly is de-oiled and dried to be disassembled into transportation units such as a core or windings. For transportation mass (including a trailer), the largest item is the U shape core of approximately 60 t. In the case of the trailer transportation, transportation permits must be prepared in advance.
- (ii) On-site assembly Conditions and Layout - The dust-proof house erected at the site has an open ceiling so that mobile cranes are used to assemble a transformer. Therefore, it is necessary to suspend the work during rain or depending on the weather. Figure 2.5 shows the erection work of a core. Two large size heavy machines are required necessitating the space of at least 800 m² adjacent to the dust-proof room. Thus, Phase1 work method has risk for weather delay and requires a large space at the site. A series of the process of the on-site transformer assembly from the shop disassembly, transportation and on-site assembly is shown in Figure 2.5.



(a) Factory test

(b) Core dis-assembly
(U-shape core)

(c) Transport (core)



(d) Transport (windings)



(e) Installation of bottom tank

(f) Lifting of core by 2 cranes
(400 t and 100 t)

(g) Installation of core by crane



(h) Insertion of windings by crane



(i) Inserting top yoke laminations



(j) Insertion of middle tank



(k) On-site assembly completed

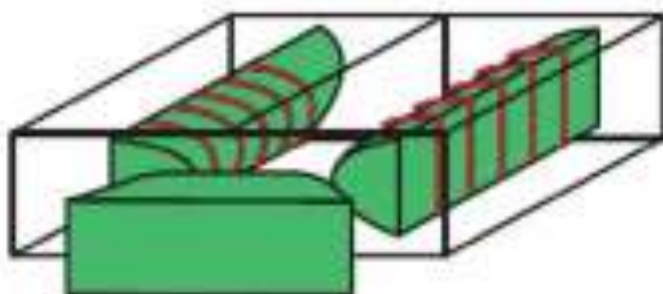
Figure 2.5 - Dismantle and re-assembly process (Phase 1)

(3) On-site assembly work procedure (Phase2) (2007~)

(i) Transport mass segmentation

Transport permits are required for heavy weight materials by road trailer. In the case of the on-site assembly transformer Phase 1, permits were necessary since the transportation weight of the cores was 60 t.. In 2007, the transport of 50 t or less was simplified in Japan and this led to the development of reducing the transport masses in on-site assembly to 50 t or less. .

- a) Core construction - The core was transported in a dedicated tank by further dividing the conventional U shape core into the leg core and the lower yoke. This simplified core binding method minimized core displacement during transport and the transportation weight of the core was able to be reduced. In addition, the transport tank of the core leg also serves as the lifting tank at site which enables the U shape core to be restored. Figure 2.6 (a) shows a segmented state of core and Figure 2.6 (b) shows the erected state at the site.
- b) Winding construction - Reduction of the transportation weight was realized by simplifying the transportation configuration within the tank and reducing the tank weight by using aluminium for the tank material.



(a) Core segmented state (Phase2)



(b) Core erected state (Phase2)

Figure 2.6 - Core segmented state and core erected state

(ii) Development and application of all-weather type internal assembling work process

Dust-proof houses used for on-site assembly were initially open ceiling type but had the disadvantage of being weather dependent. Based on this, in the Phase2 on-site transformer assembly, the all-weather dust-proof house was developed and the indoor assembly process not requiring the heavy machine crane was developed. Comparison of dust-proof houses is shown in Table 2.4.

- a) Core erection - After connecting the leg core, the lower yoke is assembled to complete the U shape core. Then, the core is erected by using the gantry lifter placed in the dust-proof room. It can be erected by using only the gantry crane so that it can be done within the dust-proof house realizing better space efficiency. The erection process of the core inside the dust-proof house is shown in Figure 2.7 (b).
- b) Assembly of internals - This time, the dust-proof house has the assembly room and the second house holds the 450 t heavy lift machine and gantry lifter capable of lifting heavy weight materials of 60 t for the indoor assembly work. The lid where the equipment can be brought in by the heavy machine was provided on the ceiling part of the second house. For this work procedure, the equipment is carried into the second house to be disassembled in such a way that it can be lifted. Then the assembly of the transformer is performed by using the gantry lifter. The equipment is placed in the transport tank when it is delivered. There are no weather interruptions for disassembly and assembly work as the second house top part is closed. Due to this, the work becomes possible during rainy weather without exposure to wind and rain except for the time when materials are carried in. Figure 2.7 shows the assembly process of internals.

Table 2.4 - Dust-proof on-site assembly house

Type	With open / close roof top type	All weather type
House appearance photo		
Structure Characteristics	Open and close the bellows ceiling of the upper part, carry in parts	No ceiling opening. Brought in parts with slide device
Transformer assembly	Parts carry-in and unpacking are carried out in outdoor environments, quality assurance, processes are affected	Parts carry in and carry out assembly without exposure to outside air



(a) Installation of bottom tank



(b) Erecting of core tank by lifter



(c) Insertion of windings by lifter



(d) Insertion of windings by lifter



(e) Inserting top yoke laminations



(f) Insertion of middle tank

Figure 2.7 - Re-assembly process (Phase 2)

2.1.3 Experience B with Shell Type

2.1.3.1 Application trend of on-site assembly transformer

In recent years, the application of on-site assembly transformers is increasing. Figures 2.8 and 2.9 shows production results of company B from 1978 to 2017.

As a background, the disassembly for transport application is increasing as transport constraints become more severe each year. In recent years, the capacity (MVA) of transformers for 500 kV substations and transformers for hydroelectric power plants has been able to increase due to compact and lightweight transportation.

Applying disassembly for transport not only solves transport constraints but also reduces installation footprint and losses.

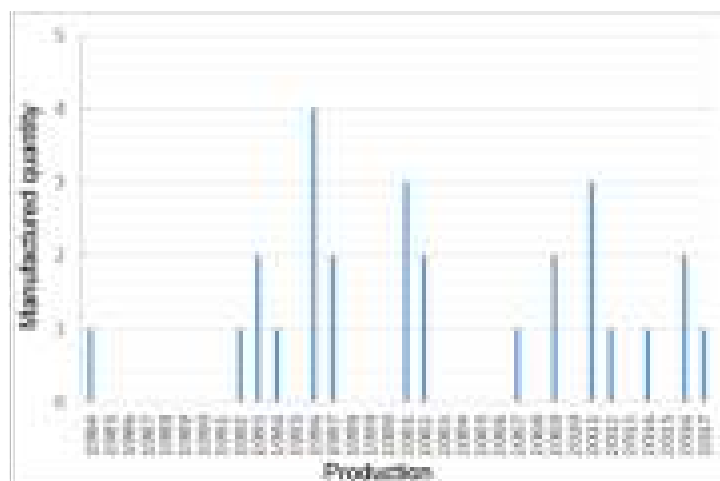


Figure 2.8 - Production experience of on-site assembly transformer (Shell Form)

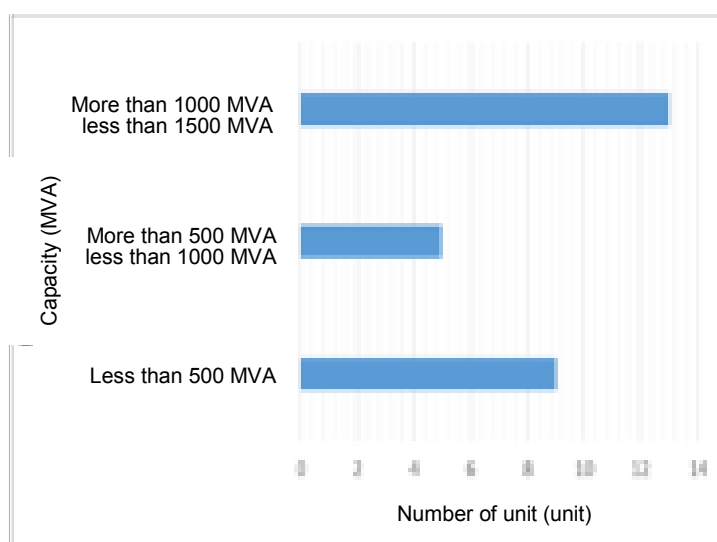


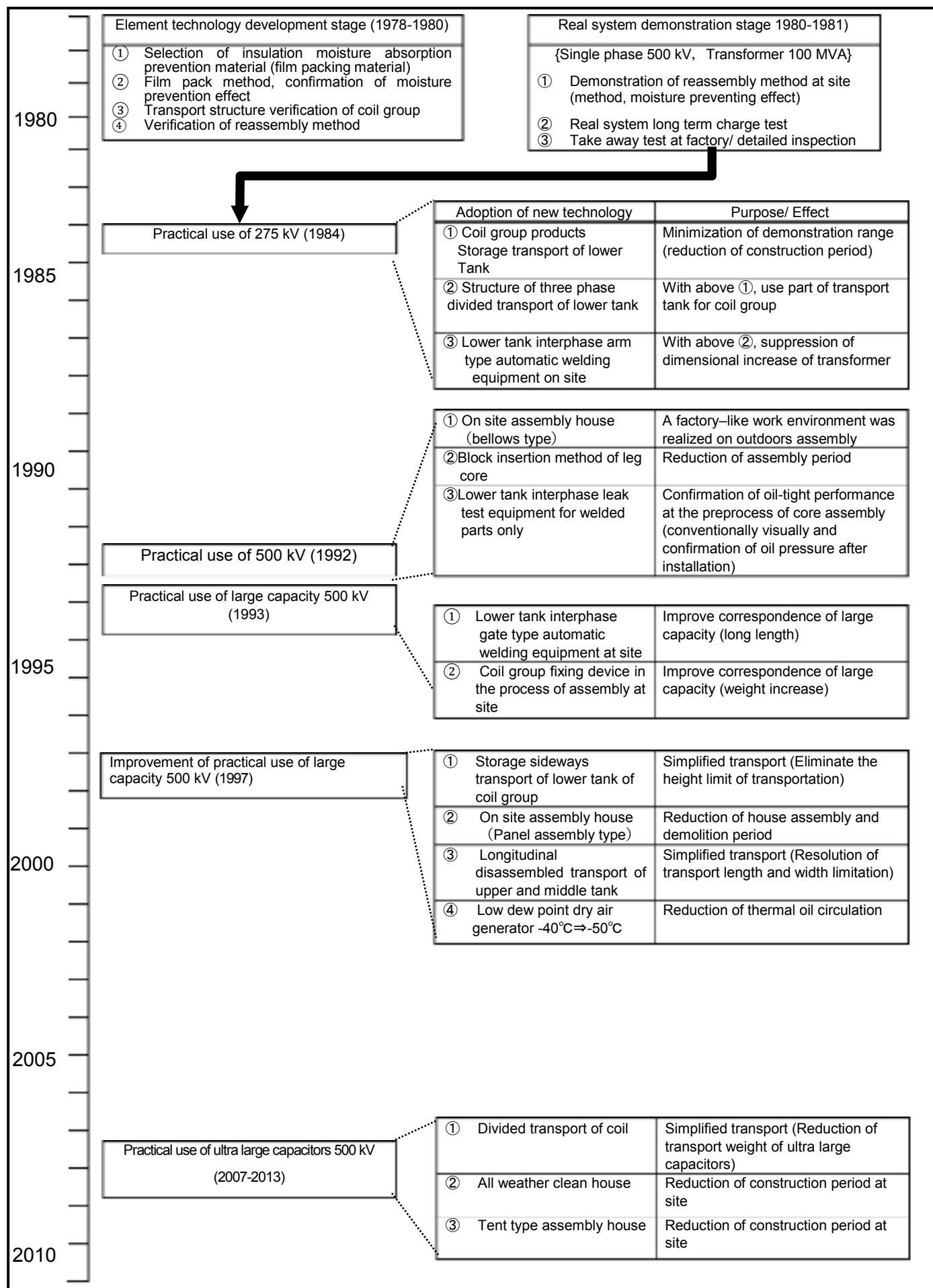
Figure 2.9 - Number and Capacity of On-site Assembly Transformers (Shell Form)

2.1.3.2 Technology transition

Table 2.5 shows the technology transition of Company B's disassembly for transport transformer.

Because the on-site assembly of a transformer involves work that exposes solid insulation to the air at site, it is necessary to prevent moisture absorption of insulation and strengthen dust control from the viewpoint of securing quality. For this reason, coil film pack technology and clean house technology was established. Also, when working inside the transformer tank and clean house, dry air with low dew point is applied to prevent moisture absorption of insulation.

Table 2.5 - Technology transition of on-site assembly transformer



2.1.3.3 Technology of on-site assembly transformer

(1) Basic structure of shell type on-site assembly transformer

Figure 2.10 shows the basic structure of Company B's shell type on-site assembly transformer. The coil group is covered with moisture absorption prevention pack film, placed in the transport tank and transported by trailer. The core is film packed in blocks and transported by truck.

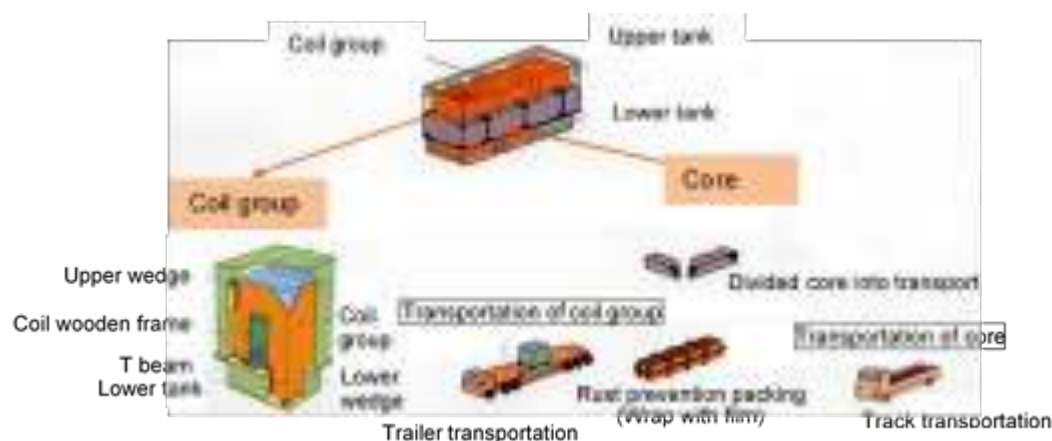


Figure 2.10 - Basic structure of Shell type on-site assembly transformer

(2) Film packing method for moisture absorption prevention of coil group

In the element technology development started in 1978, ETFE (Ethylene Tetra Fluoro Ethylene type film) was selected for excellent in moisture permeability, mechanical strength, sealing processability, oil resistance and electrical characteristics. (Figure 2.11)



Figure 2.11 - Coil group film packing

(3) Block insertion method for leg core

When transporting the shell type transformer core to site, the yokes and legs are disassembled into separate block units for transportation. To minimize field assembly time, each core leg block is re-inserted using a winch (see Figure 2.12).

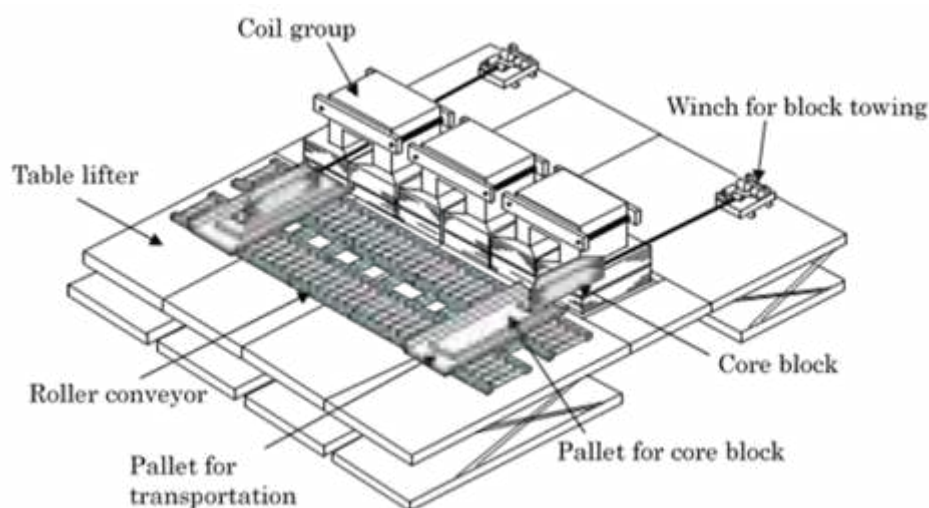


Figure 2.12 - Block insertion method of core leg

(4) On-site assembly house (clean house)

Initially a bellows type house was used but now either panel type clean house (Figure 2.13) or a tent type clean house (Figure 2.14) is selected according to local conditions and the size of the transformer.

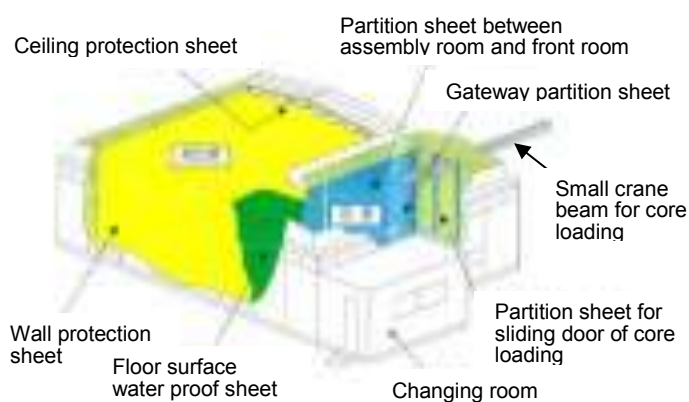


Figure 2.13 - Panel type clean house

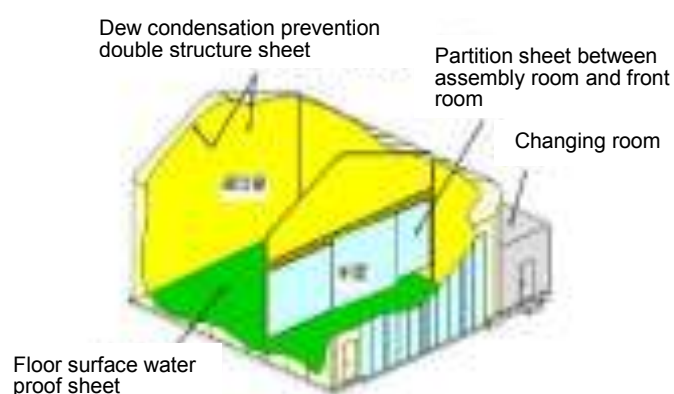


Figure 2.14 - Tent type clean house

(5) Longitudinal division of upper and middle tank for transport

Reduction of transport length and width dimension was done by dividing the upper tank and middle tank vertically for each phase (Figure 2.15).

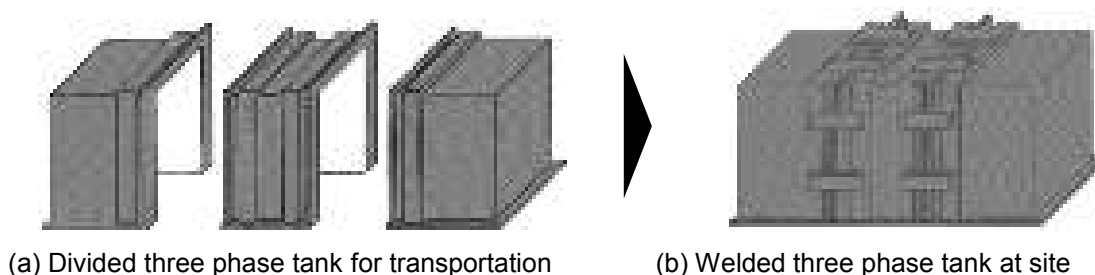


Figure 2.15 - Longitudinal division of upper and middle tank for transportation

(6) Divided coil groups for transport

Transportation mass of the large transformer is further reduced by dividing the coil group of each phase into two groups. (Figure 2.16)

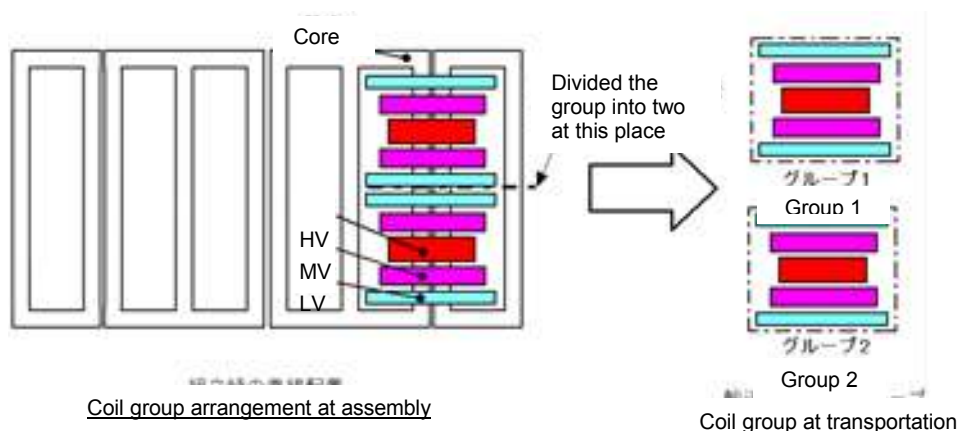


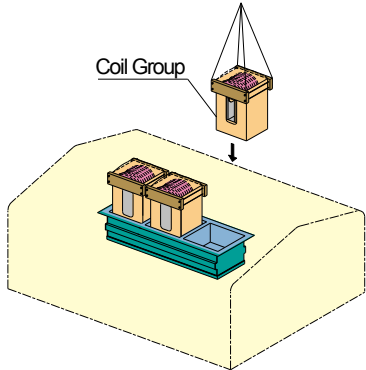
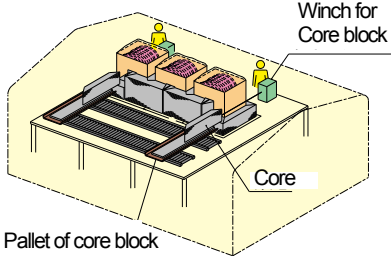
Figure 2.16 - Divided coil groups for transportation

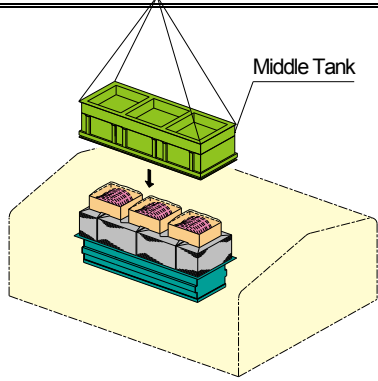
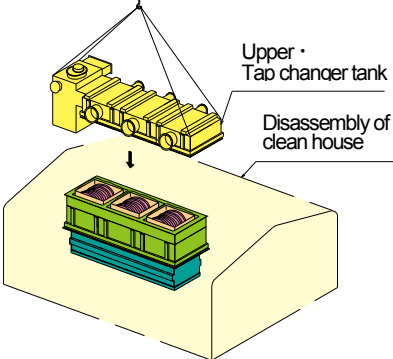
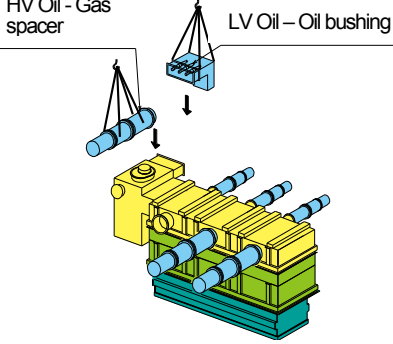
2.1.3.4 On-site assembly method and quality management

The procedure for on-site assembly and the quality management items are shown in Table 2.6. Particularly, core reassembly on site is an important point of construction of on-site assembly transformer. The quality is maintained while shortening the site process. Figure 2.17 shows shell-type application of on-site assembly transformers.

Table 2.6 - Procedure of on-site assembly and items of quality management

Major Item	Figure	Work Item	Management Item
(1) Set of clean house and bottom tank		① Set of clean house	- Humidity inside the clean house - Humidity inside the dust cover (less than 50 %) - Foreign particle - Dry air dew point (less than -50°C)
		② Receipt of bottom tank	- Visual inspection - Internal pressure - Impact level [less than 29.4 m/s²(3G)]

Major Item	Figure	Work Item	Management Item
		③ Set of Bottom tank	- Foreign particle - Dry air dew point (less than -50°C) - Weather (not rainy condition) - Flatness - Centering
(2) Set of coil group		① Receipt of coil group	- Visual inspection - Internal pressure - Impact level [less than $29.4 \text{ m/s}^2(3G)$]
		② Set of coil group	- Dimension check - Visual inspection - Foreign particle - Dry air dew point (less than -50°C) - Number of all tools - Direction and position check
		③ Low Voltage Test	- Winding resistance measurement - Insulation resistance measurement - Water content in insulation materials ($0.5 \% \cdot \text{wt.}$)
(3) Core stacking		① Receipt of core	- Visual inspection - Impact level [less than $29.4 \text{ m/s}^2 (3G)$]
		② Insert of Leg block	- No abnormality - Core stack height measurement - Foreign particle - Dry air dew point (less than -50°C) - Number of all tools
		③ Low Voltage Test	- Voltage ratio measurement - Short-circuit impedance measurement - No-load current measurement - Insulation resistance measurement between core blocks

Major Item	Figure	Work Item	Management Item
(4) Middle tank assembly		① Receipt of tank	- Visual inspection - Internal pressure - Impact level [less than 29.4 m/s² (3G)]
		② Middle tank assembly	- Foreign particle - Dry air dew point (less than -50°C) - Weather (not rainy condition) - Weather (humidity less than 80 %)
		③ Welding of Tank Flange	Weld leg length check
(5) Upper tank Assembly Disassembly of clean house		① Upper tank Assembly	- Foreign particle - Dry air dew point (less than -50°C) - Weather (not rainy condition) - Humidity (less than 80 %)
		② Vacuuming of tank , N ₂ filling and welding of tank flange	- Degree of vacuum - Internal N₂ pressure check - Weld leg length check
		③ Repair paint	Visual check
(6) External Assembly		① External assembly	- Weather (not rainy condition) - Weather (humidity less than 80 %) - Tightening torque - Visual inspection of cooling equipment - Dry air dew point (less than -50°C) - Number of all tools
		② Repair paint	Visual check

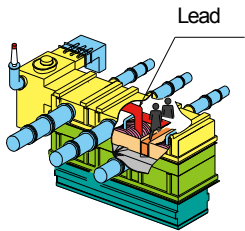
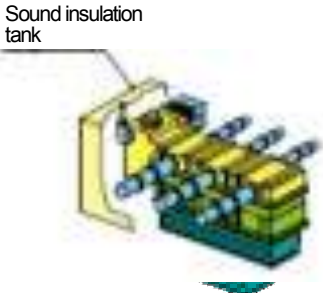
Major Item	Figure	Work Item	Management Item
(7) Internal Connection		① Internal Connection	- Weather (not rainy condition) - Humidity (less than 80 %) - Tightening torque check - Foreign particle - Check of connection and insulation work - Dry air dew point (less than -50°C) - Number of all tools
(8) Final filling the oil and site acceptance tests		① Oil filling under vacuum	- Check of insulation oil - Check of degree of vacuum (67 Pa) and holding time - Check of oil-treatment - Check of dielectric characteristic of oil (60 kV/2.5 mm) - Check of water contents in oil (less than 10 ppm · wt.) - Check of quantity of gas in oil (less than 0.5 % · vol)
		② On-site acceptance test (low voltage test)	- Voltage ratio measurement - Short-circuit impedance measurement - Capacitance, and dissipation factor ($\tan\delta$) measurement - Insulation resistance measurement - Oil tightness check - No-load current measurement



Figure 2.17 - On-site assembly transformer after completing its installation (500 kV - 1 000 MVA)

2.1.4 Experience C with Core Type

2.1.4.1 Needs and History

Company C began on site assembly with 230 kV, 135 MVA transformers delivered to mountainous areas in the 1950's. They were assembled and tested at the factory, disassembled for transportation, and re-assembled at site. In the 1980's, development of on-site assembly technology for new demand was carried out and the application was expanded [3] .

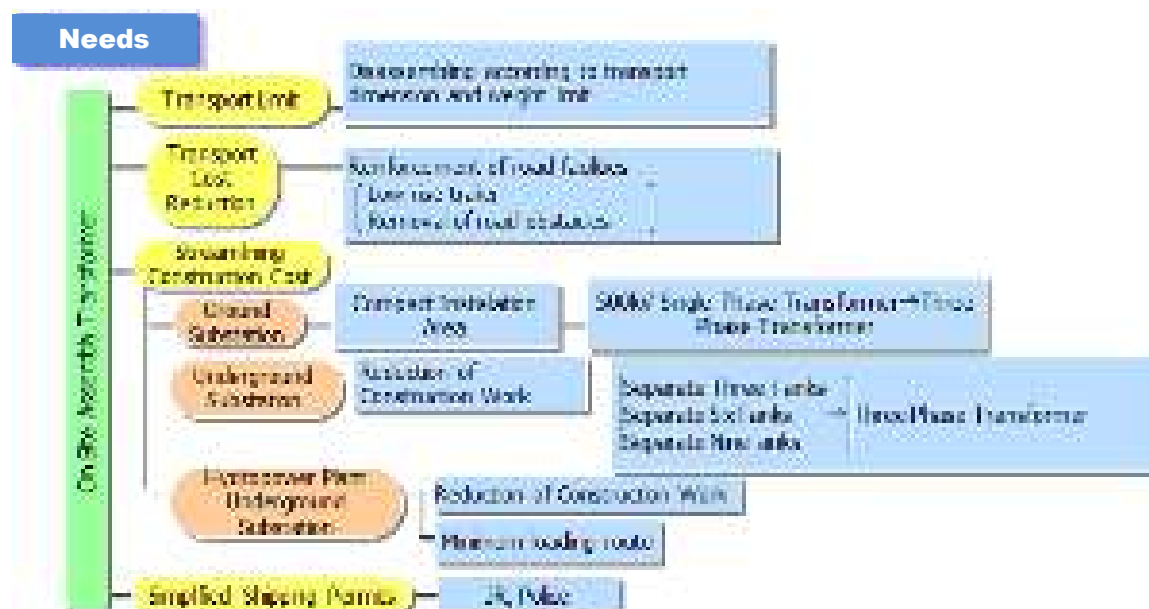


Figure 2.18 - Needs of On-site assembly transformer

Figure 2.18 shows the needs of on-site assembly technology. For company C, the application for on-site assembly of transformers started as a solution to achieve Total Cost Minimum as demanded in the transformer market. The idea of on-site assembly is to cut down the overall cost by reduction of transportation costs and minimizing the capacity requirement during site assembling.

An extensive study of on-site assembly of transformers related research such as core splitting/assembling methods, evaluation of film pack material developments etc. was carried out in the late 1980's. The results of these studies were implemented in 220 kV, 250 MVA transformers that were delivered in 1989.

These applications were continuously adopted up to 500 kV class with new materials for film packing and revised site assembling methods to improve the on-site assembly technology. Pilot tests were successfully performed in 1999 to 2000 using a 1 Phase 1000 MVA 500 kV prototype model. The first transformers to apply this technology were 400 MVA 275 kV class which were delivered in 1999 to a Japanese local utility. Figure 2.19 shows the history of on-site assembly of transformers for Company C.

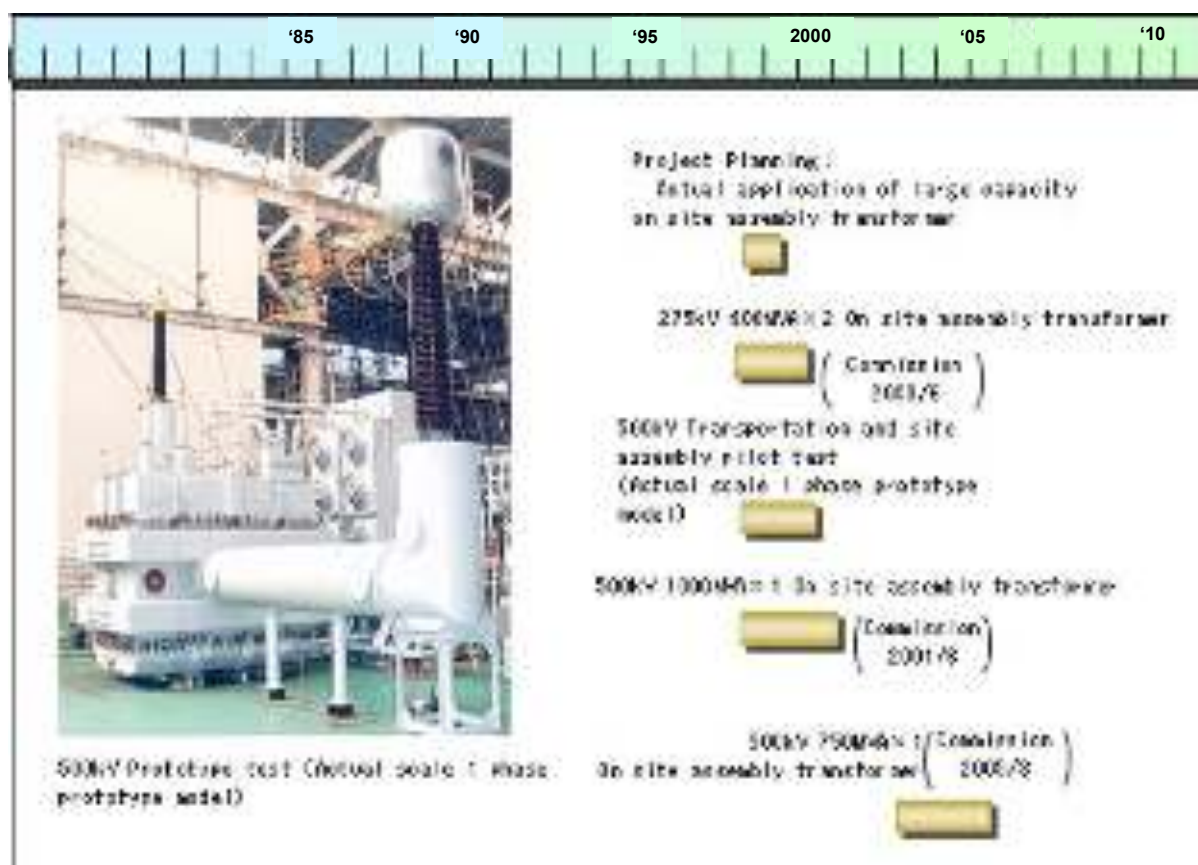


Figure 2.19 - Development of a new type On-site assembly transformer

2.1.4.2 Outline of On-site assembly Transformer

For on-site assembly, the transformer is disassembled into core, winding coil and tank components after successfully passing the factory testing. These components are re-assembled at site through strict quality control workflow. Each package of these components is designed to fit a readily available low load truck. Special design structure and manufacturing processes are applied.

The design concept is:

- 1) Minimize transport handling costs such as eliminating requirements of bridge reinforcement, utilizing low-loader trucks and keeping transport package weights below 40 t.
- 2) Maximize site work efficiency by minimizing number of transport package.

On-site assembling work requires a controlled house (Clean House), where winding and lead wire connections and tank cover installation are performed. Upon installing the tank cover, assembly work shall be performed as per a normal transformer installation (i.e. accessories, oil impregnation, final site tests etc).

Figure 2.20 shows the transporting structure of a disassembled transformer. The transformer is generally divided into three main components for transport, - core, winding and tank structure.

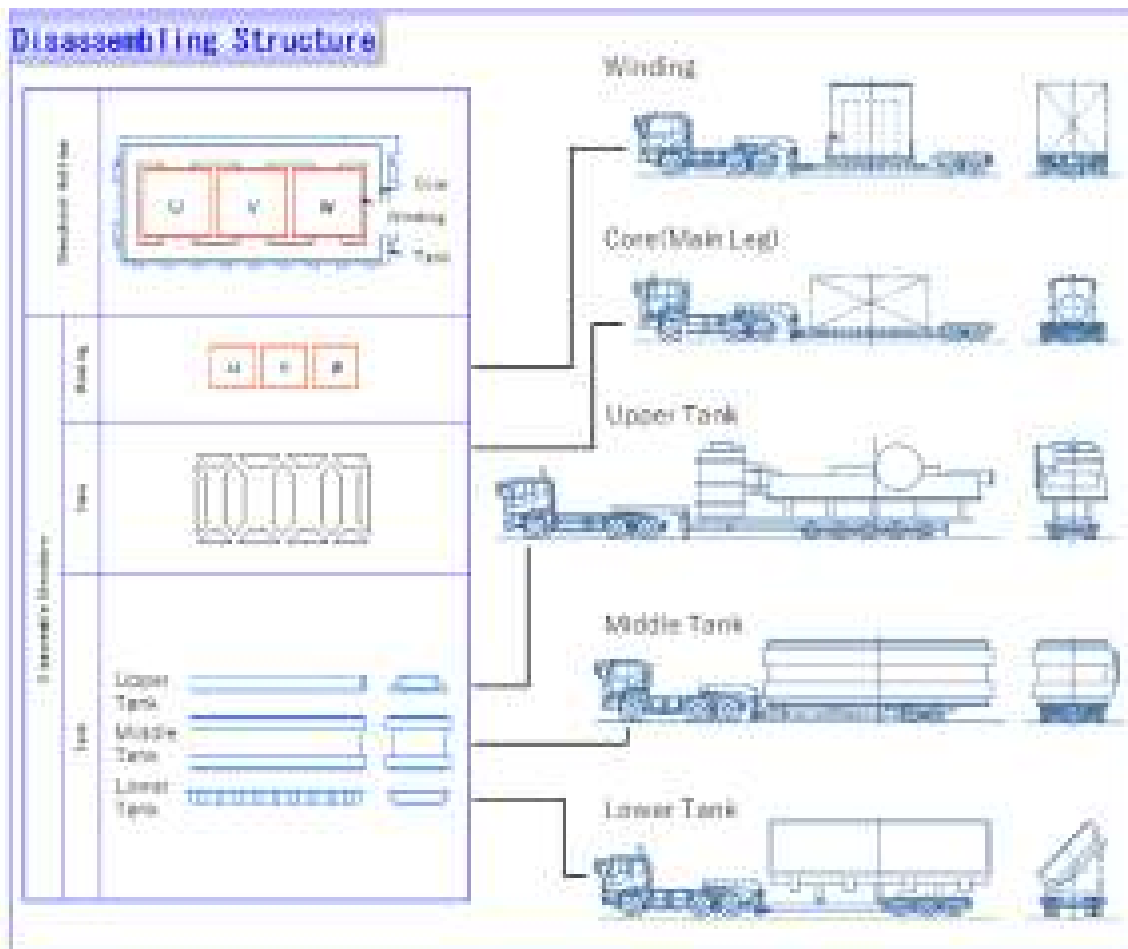


Figure 2.20 - Disassembled Components for transportation

(1) Core Structure

The core structure is divided into 13 parts (wound leg: 3 pieces, non-wound leg: 2 pieces, upper and bottom yoke: 8 pieces).

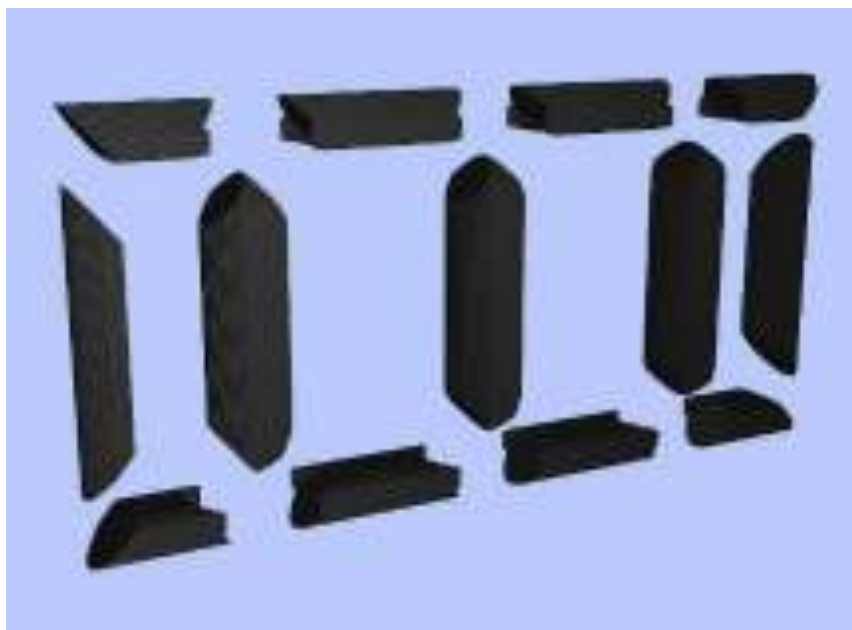


Figure 2.21 - Divided core components

(2) Winding Structure

The windings are transported in separate tanks. Each of the winding units is wrapped by special film to avoid absorbing moisture during transportation. The film is designed so that any fragments shall not remain after removing the film and degradation of insulating performance shall not occur.

Moisture in paper insulating material is securely controlled by monitoring a specimen.

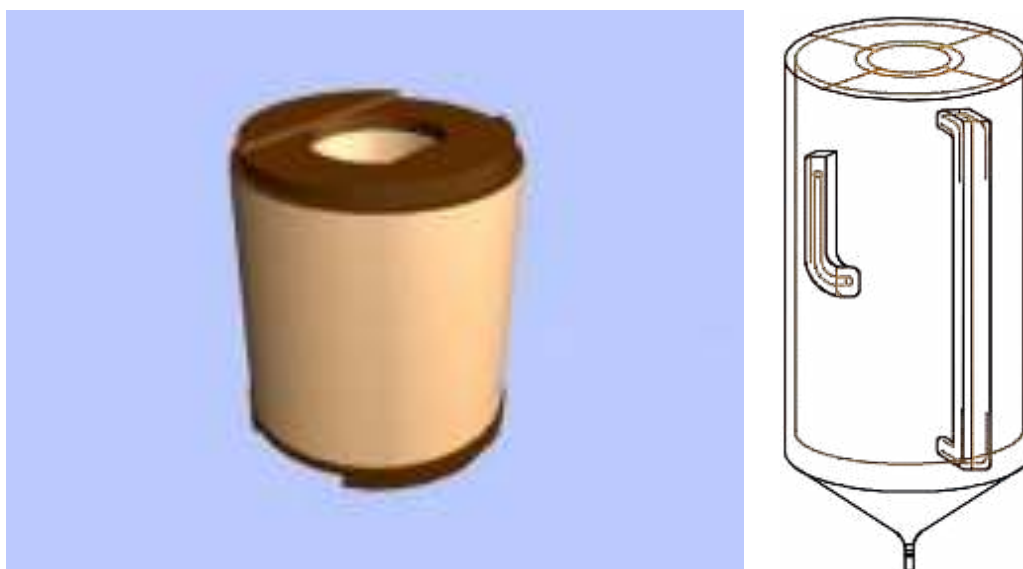


Figure 2.22 - Winding and its film packing

(3) Tank Structure

The tank is divided horizontally into 3 parts considering its transportation limit and workability at site. The tank is welded after being assembled at site.

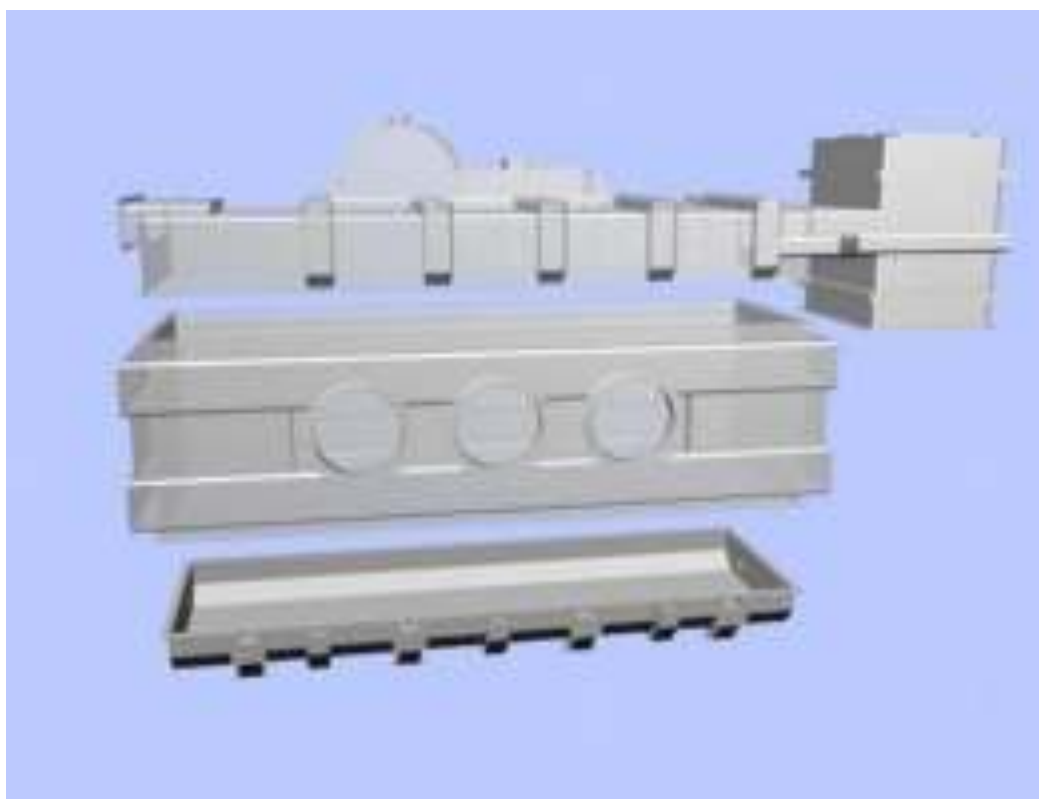


Figure 2.23 - Divided tank components

(4) Clean House

The Clean House atmosphere is controlled for humidity (less than 50%) and temperature (between 5°C and 30°C).



(a) Outside view of Clean House

(b) Inside view of Clean House

Figure 2.24 - Overview of Clean House

2.1.4.3 On-Site Work

To secure active part quality during site assembly, special quality control is considered. This especially includes prevention of moisture absorption in the insulation material and strengthening of dust proofing control. Film packing technology and clean house technology is applied. In addition, during assembly work in the transformer tank and clean house, humidity controlled dry air is blown continuously, minimizing moisture absorption in the insulation material. Figure 2.25 shows the on-site assembly work flow [4].

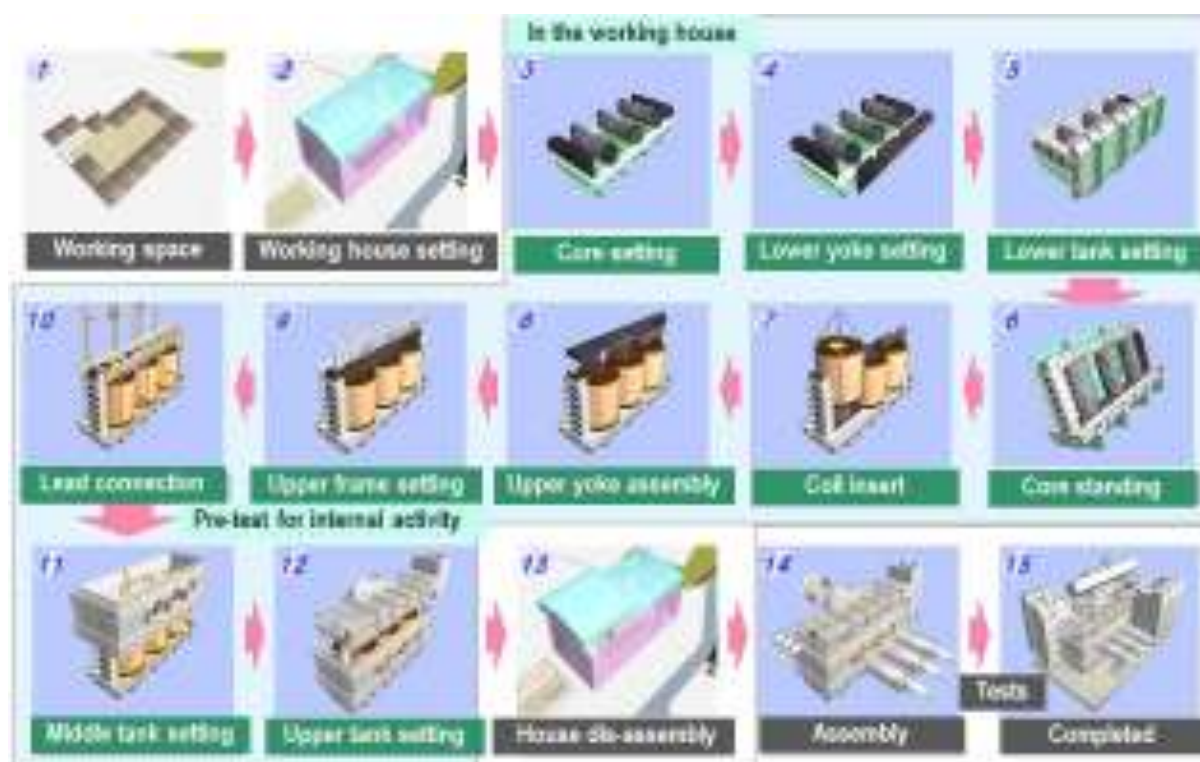
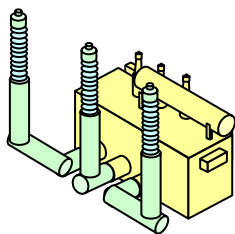
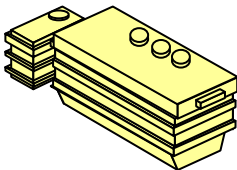
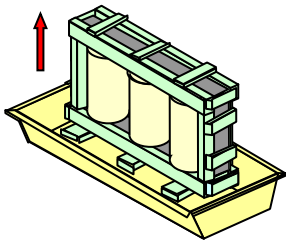
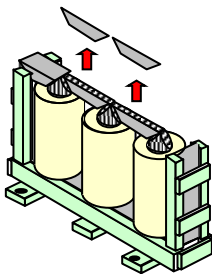
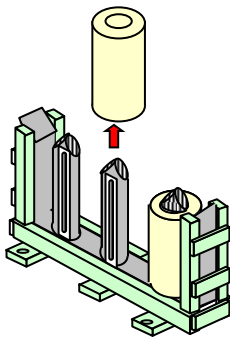
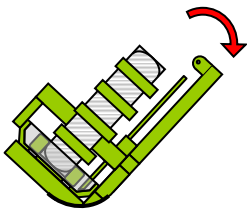


Figure 2.25 - On-site Assembly Work Flow

2.1.4.4 Quality Control for Factory to On-Site

Tables 2.7 and 2.8 show the actual quality control work flow of the on-site assembly transformers.

Table 2.7 - Disassembly Work in Factory to Shipping

Work step	Figure	Work detail
1. Factory Test		Tests will be performed according to the Inspection and Test Item (ITP)
2. Disassembly		Transformer body and accessories shall be free from damage
3. Outer Body Disassembly		(1) Dry air shall be continuously blown into the tank during work to prevent moisture absorption. (2) Dry air dew point: Below -40°C
4. Upper Yoke Removal		(1) Work shall be performed in an air conditioned, dustproof room (2) Cover the coil with dustproof, moisture proof film pack (3) Dry air shall be continuously blown into film pack during work
5. Coil Removal		(1) Work shall be performed in air conditioned, dustproof room (2) Lifting slings shall be used (3) Load parts into special transport truck
6. Core Setting		(1) Work shall be performed using the Iron Core Stand (2) Oil shall be removed from the disassembled yoke plates (3) Load parts into special transport truck

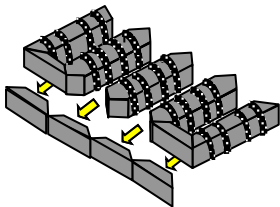
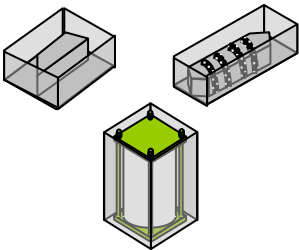
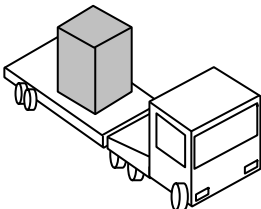
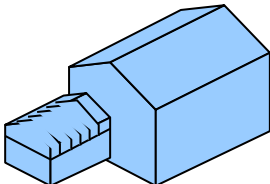
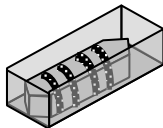
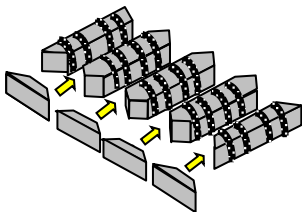
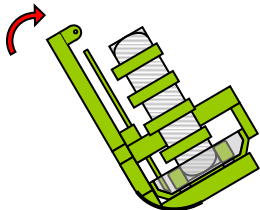
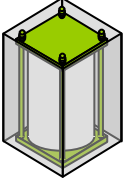
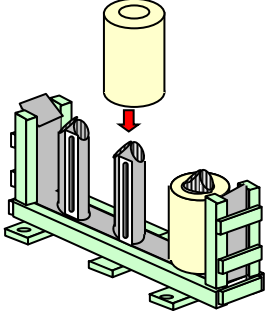
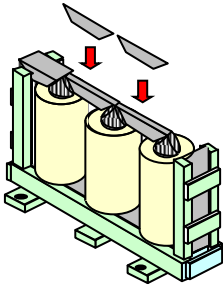
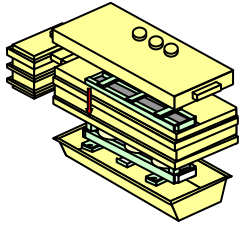
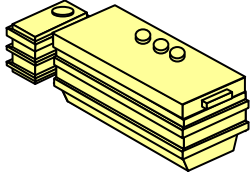
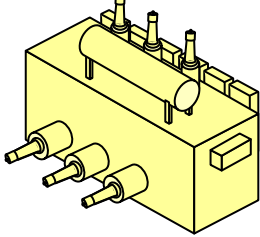
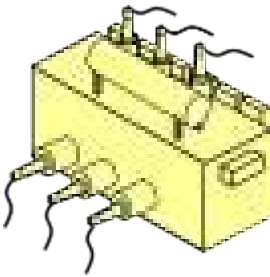
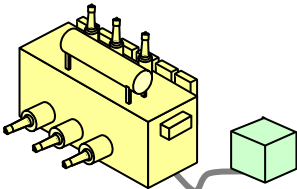
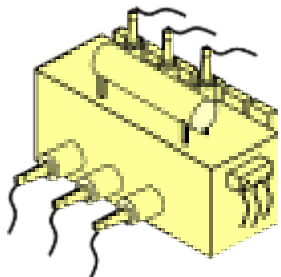
Work step	Figure	Work detail
7. Lower Yoke Removal		
8. Packing		(1) Coil, Core, Upper Yoke, and Lead Conductors shall be packed into special transport tank • Enclosed dry air dew point: Below -40°C • Enclosed pressure: 0.015 MPa (2) Install accelerometer on the coil, core tank and check for device operation (3) Check moisture content of insulating paper
9. Transport and shipping		(1) Control criteria during transportation: • Speed Limit: Below 40 km/H • Sudden acceleration & braking is prohibited (Running condition will be monitored using tachometer) (2) Acceleration: Below 29.4 m/s^2

Table 2.8 - On-Site Assembly

Work step	Figure	Work detail
1. Clean House Setup		(1) Humidity: Below 50 % RH (2) Floating dust: Below 20 cpm (3) Dry air dew point: Below -40°C (4) House Temperature: 15°C - 30°C
2. Core Leg Check		(1) Accelerometer: 29.4 m/s^2 (2) Transport tank internal pressure: Positive pressure (3) Visual check: No visible damage during transportation
3. Stacking • Tightening of Lower Yokes		(1) No overlapping between core sheets (2) Check for insulation between core and metal fittings • Insulation resistance: Below $50 \text{ M}\Omega$
4. Core Setting		(1) Leg dimension tolerance: 0 - $+5 \text{ mm}$

Work step	Figure	Work detail
5. Coil Check		(1) Accelerometer: 29.4 m/s² (2) Transport tank internal pressure: Positive pressure (3) Visual check: • No visible damage on coil film pack • No visible damage, deformation on coil (4) Check for moisture content of insulating paper
6. Coil Assembly (inserting coil)		(1) Coil must be level (2) Dry air shall be continuously blown into film pack during work (3) Dry air dew point: Below -40°C
7. Internal Assembly		(1) Stacking / Tightening of upper yoke • No overlapping between core sheets • Core insulation resistance: 50 MΩ or more (between core and fittings) • Core sheets resistance: > 0.4 Ω, less than 1 MΩ (2) Connect lead conductor • Prevent moisture absorption by film pack • Torque control of tightening parts
8. Install Upper, Middle Tank		(1) Film pack shall be removed before tank installation (2) Confirm the distance between internal body and tank (3) Check the moisture content of insulating paper
9. Tank Flange Welding		(1) Tank internal pressure: Positive pressure (2) Monitor surface temperature of tank flange (using thermo-level) (3) Check welded area using partial pressure method • Gas pressure: 0.1 MPa
10. Internal Connection, External Assembly		(1) Acceptance check of external accessories • Visual check: No visible damage (2) Internal connection and check • Tighten all fitting with suitable torque • Visual check: No visible damage • Check for insulation distance • Tank internal humidity: Below 50 %RH • Check for moisture content of insulating paper

Work step	Figure	Work detail
11. Preliminary Test		Test shall be performed according to ITP Preliminary Test Item: 1) Voltage Ratio Test 2) Core Resistance Test 3) Core Insulation Resistance Test 4) Low Voltage Excitation Current Test 5) Low Voltage Impedance Test 6) Insulation Distance Check 7) Internal Connection Check
12. Insulation Treatment		(1) Vacuuming · Vacuum pulling time: According to manufacturer's standard · Pressure: Below 67 Pa · Vacuum leakage: Below 800 Pa·ℓ /s (6 000 μHg·ℓ /s) (2) Oil Acceptance Check · Water content in oil: Below 30 ppm · BDV: 40 kV/2.5 mm or more (3) Oil Injection Characteristics · BDV: 50 kV/2.5 mm or more (4) Oil Final Characteristics · Degassing cycle: 3 cycle or more for all oil volume (2 cycle or more is required as per "Electric Technology Research Association (ETRA)"[2]) · Water content in oil: Below 10 ppm · BDV: 60 kV/2.5 mm or more · Gas content in oil: Below 0.5 % · Moisture content of insulating paper: Below 0.5 % (5) Oil Tightness Test · 0.03 MPa or more (0.02 MPaG or more x 24 h Pressurized) (6) Oil Level Adjustment · Oil level adjustment according to oil temperature and oil level curve.
13. Tests after Assembled		Test shall be performed according to ITP After Oil Filling: 1) Winding Resistance Test 2) Polarity and Phase Test 3) Insulation Resistance Test 4) Tank Pressure Test 5) Oil Water Content Analysis 6) Operational Check (OLTC) Final Assembly Test Item: 1) Dimension Check 2) Oil Tightness Test 3) Oil Water Content Analysis 4) Tan δ Test 5) Flow Electrification Test 6) Fan Control Input Test 7) Test on Control Cubicle, Accessories (Bushing, BCT, etc.) 8) Sequence Check

2.1.5 Summary

Although each manufacturer has different quality control details, the minimum quality management items and quality control standards from factory to on-site assembly are summarized in Technical Guide No.69-2 ETRA (Electric Technology Research Association) in Japan titled “Survey of applied experience for quality control of disassembly, transportation and site assembling of power transformer” published in Aug. 2013 [2] . This is referred to below. In the past 30 years, Japan has experienced a large number of on-site assembly transformers as shown table 2.9. These transformers are all in service without any major accident or failure. Presently it is very common to apply the 500 kV class to the on-site assembly transformer in Japan [5] .

Table 2.9 - Experiences of the on-site assembly transformers in Japan

Experiences of the on-site assembly transformers in Japan between 1980 and 2020			
No.	Voltage	Units	Remarks
1	500 kV	54	
2	220 – 275 kV	31	
3	110 – 154 kV	5	
4	Total	90	All transformers in service

As shown in Table 2.10, on-site-assembly transformers are controlled so that factory assembly quality is maintained from factory disassembly to on-site assembly including moisture absorption in each process. To prevent moisture absorption affecting insulation performance, a film pack is attached from the factory to the site assembling, and a clean house is installed to realize a working environment such as humidity and particle control equivalent to that of the factory. Furthermore, to confirm the moisture absorption of the solid insulation in the process of transportation and site work, a moisture absorption monitoring material is attached at the factory, and the amount of absorbed moisture in each process is managed. This is detailed in Table 2.11, 2.12, 2.13, and 2.14. Details of tests at each step are shown in Appendix A “Detail of the factory and on-site tests methods for the on-site assembly transformers in Japan”.

Quality control, especially in the field assembly work, is very important. At each point, such as at the time of core, coil assembly, etc., a unique test as shown in Table 2.14 is conducted. It is effective in ensuring the quality of these products and minimizing the process loss due to reversion work.

To further study the on-site assembly transformer, Japanese power utilities, including hydro utilities, investigated the number of incidents involving on-site assembled transformers between 1980 and 2020. No incidents were observed and only faults due to either machine aging or lack of maintenance occurred. In addition, separate three phase bank transformers, which are largely supplied, showed records of fault due to natural phenomenon or lack of maintenance to cooling units, which is not related to fault causes.

Thus, the quality control standard for work performed for on-site assembly transformer and separate three phase transformer is ensuring transformer reliability. Moreover, no faults / incidents accidents were observed from overhaul projects.

Table 2.10 - Principal quality control items for on-site assembly transformer

No	Quality control item	Contents
1	Disassembly work at the factory	- Visual inspection of coil, core, lead and internal activity - Number of parts check
2	Transportation (Record and check)	- Internal pressure of transportation tank - Impact level
3	Assembly condition at the site (Equivalent condition with the factory)	- Keep the level of humidity and foreign particle in the clean house
4	Prevention from moisture absorption in the	- Windings film packing

No	Quality control item	Contents
	insulation materials	- Dry air blowing - Moisture content measuring by monitoring insulation materials
5	Prevention from foreign particle and damage	- Protective covering - Visual inspection
6	No abnormality check of assembly parts	- On-site inspection and test

Table 2.11 - Process and quality management of 500 kV on-site assembly transformer under the factory desassembly work

Process	Management item	Criteria	Remarks
1. Oil drain	• Residual oil check	• No residual oil	
2. Dry air substitution	• Dry air dew point	• Below criteria	Depend on manufacture's criteria
3. Disassembly of external parts	• Visual inspection	• No abnormality	
	• Number of external parts check	• No missing	
	• Foreign particle check	• No abnormality	
	• Packing condition check	• No abnormality	
	• Dry air dew point	• Below criteria	Depend on manufacture's criteria (Lead compartment)
	• Internal pressure	• Positive pressure	(Lead compartment)
4. Tank disassembly	• Visual inspection	• No abnormality	
	• Foreign particle check	• No abnormality	
	• Transportation cover clamping	• No abnormality	
	• Dry air dew point	• Below criteria	Depend on manufacture's criteria
	• Internal pressure	• Positive pressure	
5. Internal activity lifting	• Visual inspection	• No abnormality	
	• Dry process condition check	• Dry condition of insulation materials surface	Not applicable depend on manufacturer
6. Internal lead disassembly	• Visual inspection	• No abnormality	
	• Foreign particle check	• No abnormality	
	• Packing condition check	• No abnormality	
	• Number of leads check	• No missing	
	• Dry air dew point	• Below criteria	Depend on manufacture criteria
	• Internal pressure	• Positive pressure	
7. Core disassembly	• Visual inspection	• No abnormality	
	• Number of disassembly core and insulation parts check	• No missing	
	• Layer and insulation resistance measurement	• More than 10 MΩ	Not applicable depend on manufacturer

Process	Management item	Criteria	Remarks
	• Dry process condition check	• Dry condition of materials surface	Not applicable depend on manufacturer
	• Foreign particle check	• No abnormality	
	• Packing condition check	• No abnormality	Not applicable in case of using the sealed transportation tank
	• Transportation tank and fittings clamping	• No abnormality	
	• Dry air dew point in transportation tank	• Below criteria	Depend on manufacture's criteria
	• Internal pressure in transportation tank	• Positive pressure	Not applicable in case of using the sealed transportation tank
8. Winding disassembly	• Visual inspection	• No abnormality	
	• Attachment of moisture monitoring insulation materials	• Done	
	• Windings drying	• Done	Not applicable for some manufacturers
	• Film packing of windings	• Done	
	• Visual inspection after film packing	• No abnormality	
	• Insulation resistance measurement	• As per Fig 9 in Oil-immersed transformer test guideline, Technical Report of IEEJ, Part II, No. 119, page 7 [6]	
	• Transportation cover clamping	• No abnormality	
	• Foreign particle check	• No abnormality	
	• Dry air dew point	• Below criteria	Depend on manufacture's criteria
	• Internal pressure in transportation tank	• Positive pressure	

Note: It is carried out when moisture absorbed by the dismantling work is removed. Depending on the manufacturer, it may be unnecessary to check the moisture content on the moisture absorption monitor material or to dry the coil before the factory test.

Table 2.12 - Process and quality management of 500 kV on-site assembly transformer during transportation

Process	Management item	Criteria	Remarks
1. Transportation	• Installation of impact recorder	• Done	
	• Internal pressure in transportation tank	• Positive pressure	
	• External condition at loading and un-loading	• No abnormality	
	• Transportation speed	Normal road • Below 40 km/h	Reference
		Highway • Below 70 km/h	Reference
	• Impact record	• Below 29.4 m/s ²	

Table 2.13 - Process and quality management of 500 kV on-site assembly transformer at on-site work

Work item	Management item	Criteria	Remarks
1. Clean house installation	• Humidity in the house	• Below 50 % (Below 80 % when ceiling is open)	
	• Floating particle	• Below 20 cpm	
	• Dry air dew point by generator	• Satisfy the criteria	Depend on manufacture's criteria
2. On base	• flatness	• Satisfy the criteria	Depend on manufacture's criteria
	• Centering	• Satisfy the criteria	Depend on manufacture's criteria
3. Coil assembly (inserting coil)	• Internal pressure in transportation tank	• Positive pressure	
	• Impact record	• Below 29.4 m/s ²	
	• Visual inspection	• No abnormality	
	• Moisture content in insulation material measurement (acceptance test)	• Below 0.5 %·wt.	
	• Winding resistance measurement	• Within +/- 5 % of FAT value	measure on later stage in some cases Timing depends on manufacturer's process
	• Insulation resistance measurement	• As per Fig 9 in Oil-immersed transformer test guideline, Technical Report of IEEJ, Part II, No. 119, page 7 [6]	measure on later stage in some cases
	• Horizontal dimension check	• Satisfy the criteria	Depend on manufacture's criteria
	• Visual inspection (assembling)	• No abnormality	

Work item	Management item	Criteria	Remarks
	• Dry air dew point	• Satisfy the criteria	Depend on manufacture's criteria
	• Foreign particle check	• No abnormality	
4. Core assembly	• Visual inspection	• No abnormality	
	• Impact record	• Below 29.4 m/s ²	
	• Internal pressure in transportation tank	• Positive pressure	(In case of using transportation tank)
	• Foreign particle check	• No abnormality	
	• Protective covering condition	• No abnormality	
	• Humidity inside of dustproof cover	• Satisfy the criteria	Depend on manufacture's criteria
	• Dew point of blowing dry air	• Satisfy the criteria	Depend on manufacture's criteria
	• Foreign particle check	• No abnormality	
	• Stacked core dimension measurement	• Satisfy the criteria	Depend on manufacture's criteria
	• Visual inspection (assembly inspection)	• No abnormality	
	• Layer resistance measurement • Insulation resistance measurement	• Satisfy the criteria • Satisfy the criteria	Depend on manufacture's criteria
5. Internal lead assembly	• Internal pressure in transportation tank	• Positive pressure	
	• Impact record	• Below 29.4 m/s ²	
	• Visual inspection	• No abnormality	
	• Dew point of blowing dry air	• Satisfy the criteria	Depend on manufacture's criteria
	• Tightening torque	• Tightened by manufacturer criteria	
	• Insulation condition check	• According to the drawing requirement	
	• Dimension check (Compare with drawing)	• According to the drawing requirement on lead	
	• Connecting condition	• No abnormality	
	• Foreign particle check	• No abnormality	
	• Lead position check	• According to the drawing requirement	
6. Tank assembly	• Visual inspection	• No abnormality	
	• Internal pressure in transportation tank	• Positive pressure	
	• Impact record	• Below 29.4 m/s ²	In case of transportation with windings and/or leads

Work item	Management item	Criteria	Remarks
	• Foreign particle check	• No abnormality	
	• Weather condition	• Not rainy condition	In case of work outside the clean house
	• Weld leg length	• Satisfy the criteria	Depend on manufacture's criteria
	• Degree of vacuum • N2 density	• Satisfy the criteria • Satisfy the criteria	Not applicable for some manufacturers
	• Damage check of internal activity	• No abnormality on internal activity	
	• Weld leg length after assembly	• Satisfy the criteria	Depend on manufacture's criteria
	• Leakage check by gas pressurization	• No leakage	
7. Internal parts test	• Low voltage test	• Satisfy the criteria	Depend on manufacture's criteria
8. Clean house disassembly	• Visual inspection of transformer	• No abnormality	
9. External parts assembly	• Check external condition (acceptance test)	• No abnormality	
	• Clamping	• No abnormality	
	• Visual inspection of transformer	• No abnormality	
	• Weather condition	• No rainy day	
	• Humidity of outside air	• Below 80 %	
	• Tightening torque	• Tightened by manufacturer control value	
	• Insulation resistance measurement	• Satisfy the criteria	Depend on manufacture's criteria
10. Connecting of bushing lead	• Visual inspection	• No abnormality	
	• Internal pressure in transportation tank	• Positive pressure	
	• Impact record	• Below 29.4 m/s ²	
	• Protective covering condition	• No abnormality	
	• Tightening torque	• Tightened by manufacturer control value	
	• Insulation condition check	• According to the drawing requirement	
	• Dimension check (Compare with drawing)	• According to the drawing requirement on lead position	
	• Worker clothes check	• No abnormality	
	• Foreign particle check	• No abnormality	
	• Check number of parts and	• No missing	

Work item	Management item		Criteria	Remarks
	tools bringing in the tank			
	• Dew point of blowing dry air		• Satisfy the criteria	Depend on manufacture's criteria
	• Humidity of inside air		• Satisfy the criteria	Depend on manufacture's criteria
	• Weather condition		• Not rainy condition	
	• Humidity of outside air		• Below 80 %	
	• Connecting condition		• No abnormality	
	• Lead position check		• According to the drawing requirement	
11. Vacuum, degassing and oil filling and oil circulation	Acceptance	• Breakdown voltage	• Over 40 kV/2.5 mm	
		• Water contents	• Below 30 ppm·wt.	
	Vacuum, degassing and oil filling	• Water content measurement in insulation before vacuum	• Below 0.5 %·wt.	
		• Degree of vacuum and duration	• Satisfy the criteria	Depend on manufacture's criteria
		• Moisture content in insulation material measurement after vacuum	• Below 0.5 %·wt.	
		• Number of oil circulation for degassing	• More than 2 circulation	
		• Settling time	• More than 72 h	
	After oil filling	• Breakdown voltage	• Over 60 kV/2.5 mm	
		• Moisture contents in oil	• Below 10 ppm·wt.	
		• Gas contents in oil	• Below 0.5 %·vol	
		• Oil tightness pressure and duration	• Satisfy the criteria	Depend on manufacture's criteria
		• Moisture content in insulation material measurement after degassed oil filling	• Below 0.5 %·wt.	
		• Oil leakage check	• No leakage	
		• Oil level check	• Based on oil curve	Depend on manufacture's criteria
12. Touch-up paint	• Check Touch-up paint condition		• Done	Depend on manufacture's criteria

Work item	Management item	Criteria	Remarks
13. Finished product testing	· Electrical test	· Satisfy the criteria	Per manufacturer's criteria

Table 2.14 - Test items for on-site assembly transformer at on-site

Test item	Purpose of test
1. Winding insulation resistance	No abnormality check of windings after transportation and on-site assembly.
2. Ratio	Lead connecting work check
3. Polarity check	
4. Short-circuit impedance measurement in low voltage	No abnormality check of windings after transportation and on-site assembly.
5. Excitation test in low voltage	No abnormality check of core assembly
6. Capacitance measurement	No abnormality check of coil after transportation and on-site assembly
7. Dissipation factor measurement	Insulation materials condition check, especially moisture absorption
8. Core layer resistance/insulation resistance measurement	No abnormality check of core assembly

2.2 Experiences in Europe

2.2.1 Experience D - Mountain Transport for Hydro-electric Generator Transformer

The first example for on-site assembly transformer in Europe is from the 1990's. A transformer for the pumped storage power plant in the Alps at Kaprun Limberg (Austria) was to be delivered and installed. The transformer was 116 kV star to 10.25 kV delta connection with a 56 MVA rating and forced oil water cooling plant. The transformer was assembled and tested on-site to enable transportation to the power plant in the mountains. Figure 2.26 illustrates the power plant in Kaprun Limberg.



Figure 2.26 - Kaprun Water Storage Power Plant Limberg
(Source: German newspaper Augsburger Allgemeine)

The transformer main components were manufactured in the factory before shipment on site. The transformer was not assembled and tested in the factory before shipment on site. The core and winding blocks were assembled in the factory before shipment on site.

The winding blocks were dried and impregnated via oil spray. A temporary clamping device was used to clamp and fix the winding block during shipment. The winding blocks including a temporary clamping system were assembled and shipped inside the transformer tank.

The core was assembled completely in the factory and fixed with special supports to enable the shipment of the core. The core was wrapped with plastic foil to protect it from dust during shipment.

All auxiliary equipment such as turrets, bushings, coolers, etc. were packed in crates. All necessary tools, assembly facilities and testing facilities were packed in containers and shipped to site.

The transportation was done mainly by flat-bed vehicle. A special elevator was used for lifting of the components and materials to the Kaprun mountain middle station Lärchenwald. Figure 2.27 and Figure 2.28 shows pictures of the transportation.



Figure 2.27 - left: Road transportation of core with special low road vehicle; right: Loading of core on elevator at mountain valley station



Figure 2.28 - left: Mountain elevator to lift devices, core and tank including winding blocks to the middle station Lärchenwald of Kaprun mountain; right: transportation from elevator to power station via road transport vehicle, here: tank transportation including winding blocks

The final assembly of the transformer was performed in the power station of the water power plant. A kind of tent was installed inside the power plant housing to provide an enclosed area, encapsulated from the environment. The roof top of the tent was movable to lift components and devices inside the tent. The power station facility had sufficient crane capacity to lift all necessary devices and components including the fully assembled transformer. Further mobile air conditioning devices were installed inside the power station facility to control the ambient air for transformer final assembly. A slight overpressure was applied inside the tent to prevent contamination with dust and particles inside the tent.

First the core was put into the assembly area. Next the upper clamping arrangement and the upper yoke were removed in order to assemble the winding blocks. The winding blocks were removed from the transformer tank and assembled to the prepared core. Afterwards, the winding blocks were covered with plastic foil to prevent any contamination during yoke stacking. The lead assembly was done after finalization of yoke stacking. The active part was lifted out of the tent for tanking. Afterwards, final assembly of all external components was done. Vacuum and oil filling process was performed according to the factory processes and parameters. Figure 2.29 and Figure 2.30 shows the on-site manufacturing process.

The transformer was tested in a specially prepared area inside the power station. The area was cleaned in order to achieve required clearances and cleanliness. The test equipment was shipped to site beforehand. The following routine tests were performed to certify the transformer function and to

guarantee lifetime expectation.

- Temperature rise test (note: was performed before tanking)
- Vector Group and ratio measurement
- Winding resistance in all tap positions
- Lightning impulse testing at 440 kV on HV side (Note: corresponds to 80 % of nominal levels)
- Applied voltage testing
- No load losses testing (with temporary generator)
- Impedance measurement (with temporary generator)
- Capacitance and $\tan \delta$ measurement
- Insulation resistance measurement
- Testing of protection and control equipment
- Testing of Oil samples

The tests were performed successfully, and the transformer was put into operation.



Figure 2.29 - left: Core after upper yoke and clamping removal inside the tent; middle: Winding block fitting to the core; right: Upper yoke stacking

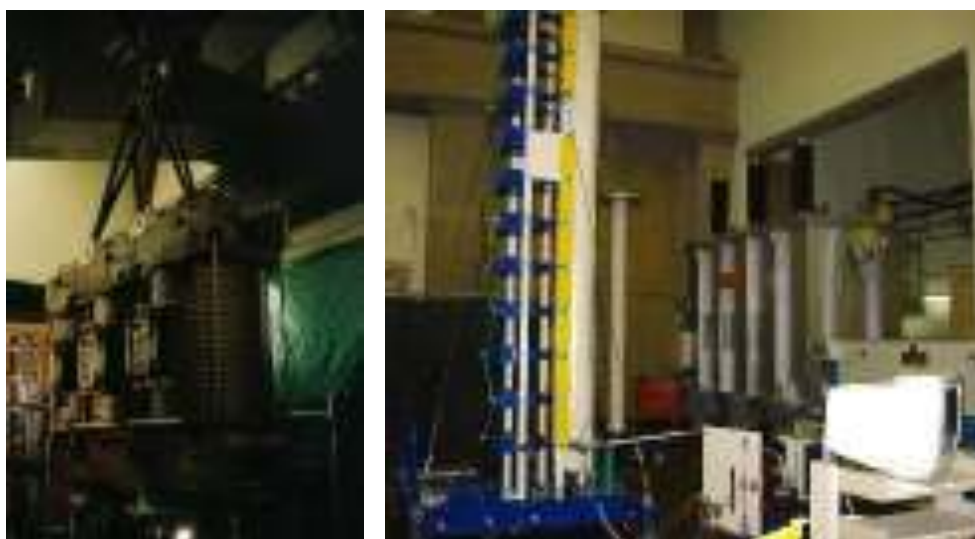


Figure 2.30 - left: Internal active part tanking; right: Transformer during impulse testing

2.2.2 Experience E - Replacement with Larger/ Heavier Transformers

This experience is described for the example of transformer replacement done in a mountainous area.

2.2.2.1 Background

The replacement transformer followed a new transformer efficiency regulation (reduced loss requirement). The replacement transformer has the same rated voltage and power, but increased weight and size. As a result, these replacement transformers need on-site assembly technology due to the severe transportation situation and limitations.

The transformer efficiency regulation in EU is shown below,

(1) Peak Efficiency Index (PEI)

Key issues are as follows:

- Relevant for transformers above 3150 kVA
- Apply new thresholds for the efficiency

The 548/2015 regulation of the EU directive targets to lower CO₂ emissions:

PEI regulation for transformer capacity > 100 MVA shown in Figure 2.31

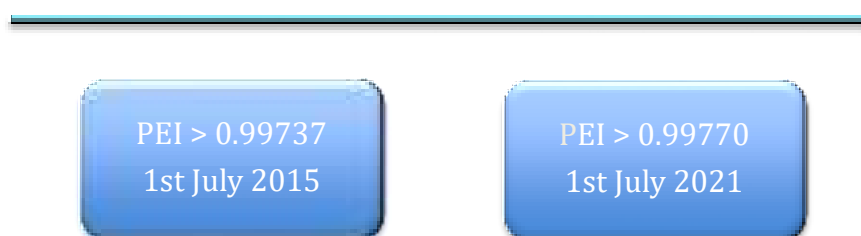


Figure 2.31 – PEI Comparison of the 2015 and 2021 EU regulation

(2) Impact to new transformers

The new transformer efficiency regulation causes loss reduction leading to an increase of transformer weight and cost as shown in Figure 2.32. The transport weight increased 30% between 2007 (step 1) and 2011 (step 3).

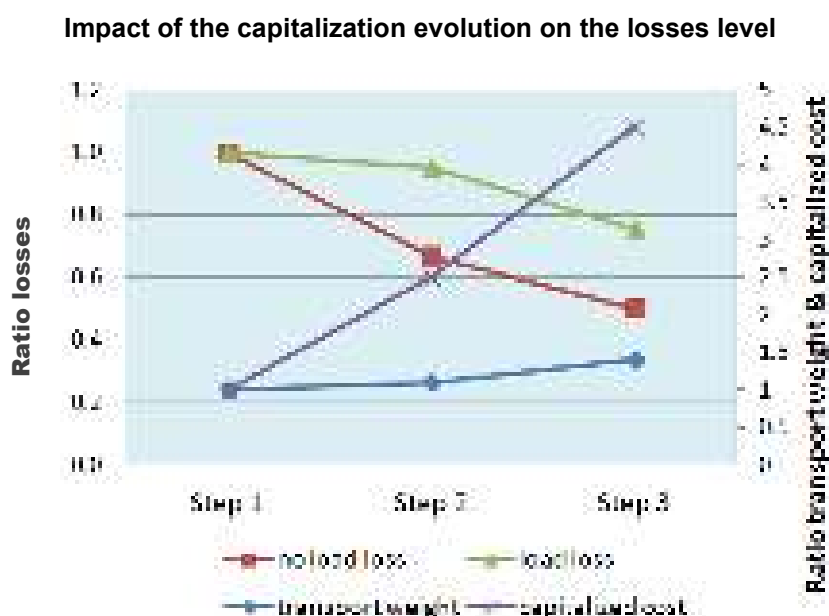


Figure 2.32 - Impacts to loss, weight and cost between 2007 (Step 1) and 2011 (Step 3)

(3) Transportation

Transportation dimensions exceed the rail limits as shown in Figure 2.33. On-site assembly transformers were then applied to the replaced transformers.

Impacts for the transportation are described as follows:

- Removal of the French railway sizing from specification
- More complex routes & logistics
 - Specific trailers / load breaks
 - Bridges, tunnels,
- Higher transport costs
- Modification of substation designs (civil work, heavy roads, access)
- Most substations no longer accessible



“On-site assembly (OSA) of Transformers” should be applied.

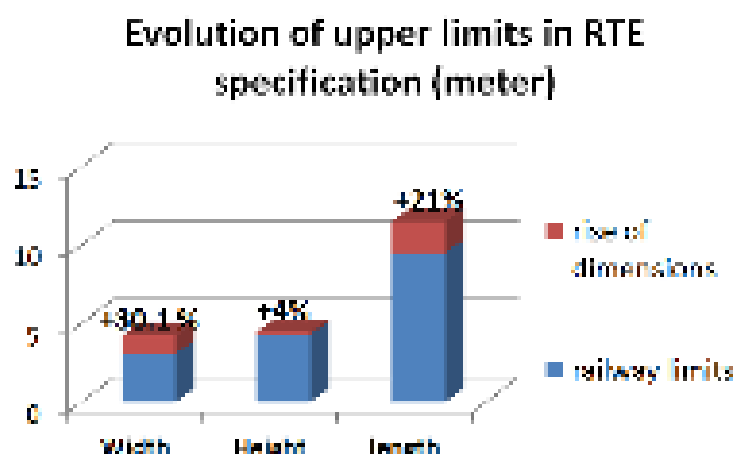


Figure 2.33 - Railway limits and over-sizing by new regulation

Figure 2.34 shows the severe situation of the transformer transportation examples.



(a) Pass under bridge

(b) Severe corner on the load

Figure 2.34 - Complexities of the transportation

2.2.2.2 Project example and User specification example

(1) RTE Example Project

Details of the example project for the transformer replacement is shown below. Figure 2.35 shows the site of this project.

- RTE « Haute Durance » Project
- First On-Site Assembly for RTE
- 3 *170 MVA - 220/66 kV YD TFO project in French Alps
- 45 t transport limitation
- Design TFO 161 t
- Project starts in June 2017
- Type tests done on 1st unit only



(a) On-site for the transformer installation (in the French Alps)



(b) Foundation of the transformer

Figure 2.35 - On-site of the transformer

(2) RTE Specification

RTE specified the following key items for applying the first on-site assembly transformers:

- Definition of OSA (On-Site Assembly)
- OSA unit must be same design as 1st unit
- Minor design adaptations can be authorized due to on site process constraints
- Considered OSA if one of the following steps is done near/in the substation rather than in factory
 - Construction of core
 - Assembly of windings on core
- Connections to bushings and tap changer
- Vacuum and oil process
- Routine tests
- Routine and type test of 1st unit in factory (mandatory)
- Routine tests only for OSA TFO
- Same quality as factory units must be guaranteed
- If unit was previously tested in factory than RTE can authorize
- New construction of magnetic circuit
- New connections

Figure 2.36 shows flow for the first unit or repeated unit.

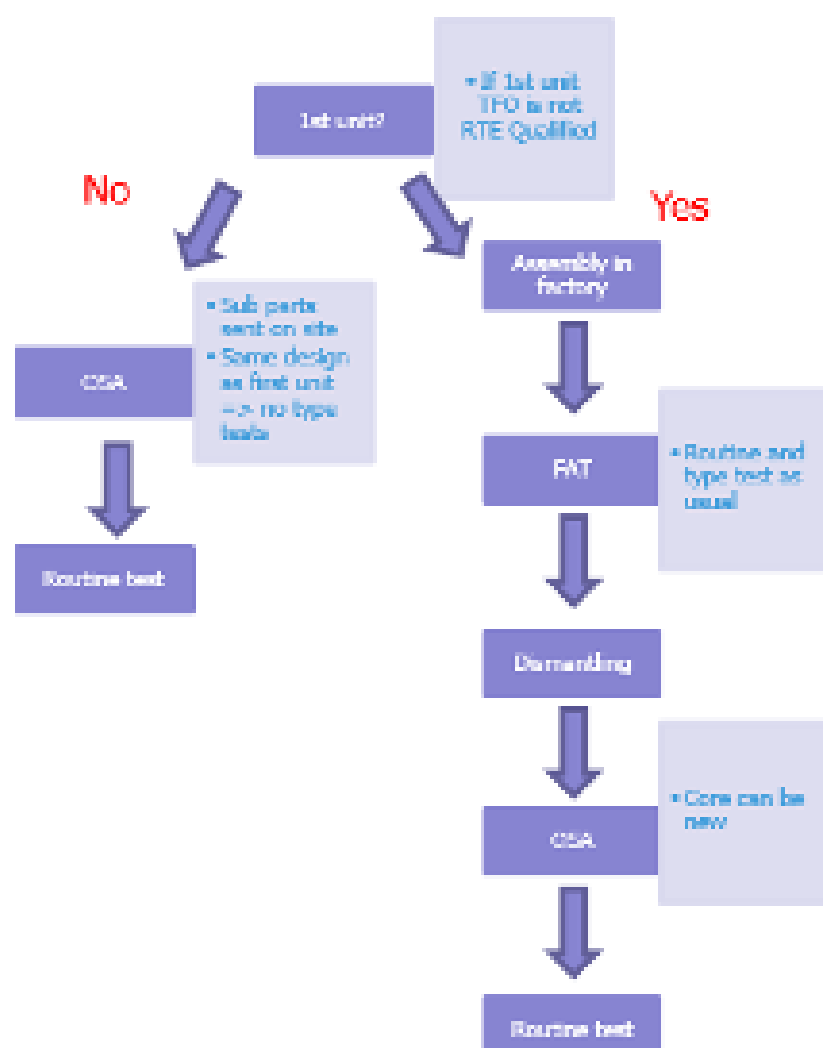


Figure 2.36 – Working flow in accordance with the unit (User Specification)

(3) On-site tests

On-site routine tests consider the site situation and condition as follows:

(i) Tests - Alternatives

- Equipment restrictions and/or environment conditions could limit
 - Impedance
 - Load Losses
- current limitations ($< \frac{I_r}{2}$) (I_r : rated current)
- IVPD
- Modification of PD thresholds (external PD impact)
- Subtract background noise during the measurement

(ii) Adapted test in order to:

- Correlate results to FAT tests
- Compare to guaranty values
- Validate tests

2.3 Experience in China (1 000 kV AC Power Transformers)

2.3.1 Introduction

As a large energy consuming country, the energy distribution of power generation and economic development in China is very uneven. Water, energy, and coal are mainly distributed in the western and northern regions, and the demand for energy and electricity is mainly concentrated in the economically developed eastern and central regions. The distance between the energy source and the energy consumption area is very long. At the same time, the demand for energy is also increasing with the rapid development of the economy. The imbalance between the energy distribution and consumption defines that the energy resource distribution should be optimized throughout the country. Through the construction of a strong national grid based on the UHV power grid, coal to electricity in situ transformation and large-scale development of hydropower had been promoted vigorously to realize coordinated development between hydropower and coal power across regions and basins. As a result, clean electricity has been transmitted from the western and the northern regions to the northern and eastern regions to meet the growing demand of electricity brought about by China's rapid economic development. Since the first UHV AC demonstration project of Jindongnan via Nanyang to Jingmen was approved to start construction in August 2006, there have been 11 UHV AC power transmission projects put into commercial operation successfully as of the end of 2017. The backbone of UHV AC power grid has been built in the vast area of Sanhua (North, Central and East China), which plays a major role in ensuring China's energy security, promoting green development and haze governance. The UHV AC transmission projects in operation increased a total power transformation capacity of 135 000 MVA and a total line length of 20 170 km including 27 UHV AC substations, one UHV AC switching station and three UHV AC fixed series capacitor (FSC) stations (see Table 2.15).

Table 2.15 - Statistics of China's UHV AC transmission projects in operation

No.	Project name	Capacity MVA	No. of UHV AC stations	Line Length km	Time of approval	Time in operation
1	Jindongnan via Nanyang to Jingmen project	6 000	3 Note 1	640 Note 2	August 2006	January 2009
2	Extension of Jindongnan via Nanyang to Jingmen project	12 000	3 Note 3		December 2010	December 2011
3	Huainan via Zhebei to Shanghai project	21 000	4 Note 4	2×648 Note 5	September 2011	September 2013
4	Zhebei to Fuzhou project	18 000	4	2×596	March 2013	December 2014
5	Huainan via Nanjing to Shanghai project	12 000	5 Note 6	2×738	April 2014	September 2016 Note 7
6	Ximeng to Shandong project	15 000	4 Note 8	2×730	July 2014	July 2016
7	Mengxi to Tianjinnan project	24 000	4	2×630	January 2015	November 2016
8	Yuheng to Weifang project	15 000	4 Note 9	2×1,050	May 2015	August 2017
9	Ximeng to Shengli project	6 000	2 Note 10	2×240	December 2016	June 2017
10	Linyi substation project	6 000	1	2×58	September 2016	December 2017
11	Extension project of Weifang substation	3 000	1 Note 11	2×75	October 2016	September 2017

Note 1: Including two substations and one switching station.

Note 2: Single transmitting line only used in those two projects.

Note 3: Including 3 extension substations and two new FSC stations, FSC stations constructed inside substations.

Note 4: Including three new substations and one extension substation.

Note 5: Double transmitting lines used from the project and follow-up projects.

Note 6: Including three new substations and two extension substations.

Note 7: Sutong GIL utility tunnel project supporting construction planned to be put into service in

October 2019.

Note 8: Including 3 substations and one new FSC station.

Note 9: Including three substations and one switching station.

Note 10: Including one new substation and one extension substation.

Note 11: Including one extension substation.

As the key equipment in UHV AC grid, a great number of success experiences have been accumulated over ten years' of UHV AC engineering practice in design, process, manufacturing, testing, transportation and installation, acceptance test, system commissioning and operation maintenance of UHV AC transformers in China. More than 150 transformers have been put into service successfully to ensure safe and reliable operation of the UHV AC grid. However, because of the limitations with transportation dimension, weight, and geographical environment, it has always been difficult for the integral transportation of UHV AC transformers filled with dry air or nitrogen. Therefore, it was necessary to carry out the R&D of UHV AC site assembled transformers for use in areas where transport conditions are particularly difficult and UHV AC transformers could not be transported as a whole or in several parts by conventional dismantling [7] [8] .

After in-depth scientific analysis, it was decided to use UHV AC site assembled transformers as a demonstration application in the Jin-Zhong UHV AC substation of a UHV AC project from Shaanxi to Shandong in China, same as Item 8 of Yuheng to Weifang project in Table 1 mentioned above. Based on the prototype R&D results of UHV AC site assembled transformer with rated capacity of single phase 1 500 MVA, and a great deal of engineering application achievements accumulated in 500 kV & 750 kV site assembled transformers of Chinese transformer factories, a general technical route for UHV AC site assembled transformers has been defined. This includes factory disassembly, split transportation, field assembly and final installation on concrete foundation with the improvement of key technologies in design scheme, disassembly and transportation technology in split parts, field assembly plant design, quality control measures of assembly process, transportation in substation after assembly is finished, installation on concrete foundation and special acceptance test items etc. Finally, the engineering demonstration application of UHV AC site assembled transformer has been realized which could be used as a feasible technical solution for transformer transportation of follow-up projects.

2.3.2 Key Technology Research

Based on technical achievements of UHV AC transformers from many successful applications in UHV AC transmission projects, R&D was carried out for UHV AC site assembled transformers. Key technology research was completed on structural type and technical parameters, modular design and production process, quality control measures of split parts transportation, field assembly plant design, assembly flow and process quality control measures and special acceptance testing methods etc.

2.3.2.1 Structural Type and Technical Parameters

The structural type of on-site assembly transformer would be the same as that of UHV AC transformers for a large number of engineering applications, i.e. a UHV AC transformer consists of a main transformer and a regulation-compensation transformer inside with different oil tanks connected by outside pipe type bus in air between two transformers. The main transformer is designed to be an assembled type including the split frame type iron core structure, complete assembly winding structure, detachable lead structure and upper and lower two sections of oil tank structure etc. The voltage regulation method at the neutral point of off-circuit tap-changer is adopted by the site assembled transformer, and the cooling method is OFAF. The on-site assembly transformer has excellent performance such as low losses, low noise and PD free etc. The parameters of the main transformer are listed in Table 2.16.

Table 2.16 - Main parameters of main transformer for UHV AC on-site assembly transformer

Items			Parameters
Rated capacity (HV/MV/LV) / MVA			1 000 / 1 000 / 334
Rated voltage (HV/MV/LV) / kV			(1 050/ $\sqrt{3}$) / (525/ $\sqrt{3}$) / 110
Voltage regulating mode		De-energized tap-changing	$\pm 4 \times 1.25$ % (9 taps)
Insulation levels kV	HV	LIFW / LICW / SI	2 250 / 2 400 / 1 800
		AC (5 min)	1 100
	MV	LIFW / LICW / SI	1 550 / 1 675 / 1 175
		AC (1 min)	630
	LV	LIFW / LICW	650 / 750
		AC (1 min)	275
	Neutral-point	LIFW	325
		AC (1 min)	140
No-load loss, P ₀ / kW (75°C)			≤180
Load loss, P _k / kW (75°C)			≤1 500
Short-circuit impedance, U _k (H-M / M-L / H-L) / %			18 / 40 / 62
Cooling type			OFAF
Noise / dB (A)			≤75

Note: LIFW-Lightning Impulse of Full Wave, LICW-Lightning Impulse of Chopped Wave, SI-Switching Impulse, AC-Alternating current with power frequency.

2.3.2.2 Modular Design and Production Process

The modular design of electrical and structural aspects has been completed which could meet the requirement of factory manufacturing, split transportation and field assembly. An independent design has been used for the core, active part, lead and oil tank. The core is designed to be three U-shaped core frames, the oil tank is divided into an upper & lower section and the main body of transformer is decomposed into different parts but excluding external components such as coolers, bushings, leads exit with ascending flanged base turrets etc. The maximum transportation weight of a single part could be about 70 - 80 t.

The disassembly process flow after factory tests is shown in Figure 2.37:

Finish all factory test items → Transformer oil discharge → Dismantling external components → Hoisting out active part and drying in furnace → Surface de-oiling treatment of active part → Fastening main body in position → Releasing pressure of main body → Dismantling leads (among HV, LV sides and columns) and wiring clamps → Dismantling upper clamp and upper yoke → Hoisting out complete assembly windings → Dismantling barrier pressboards of core limbs → Hoisting out core and transferring to core assembly area → Laying down core limbs on a roll platform → Dismantling clamps and core laminations → Refolding core into U shaped core frames → Assembling core → Transporting split parts.



(a) Assembled transformer after factory tests (b) Diagram of disassembly of each component

Figure 2.37 - Disassembly process flow of on-site assembly transformer after factory tests

2.3.2.3 Quality Control Measures of Split Parts Transportation

The transformer core could be disassembled into three U-shaped core frame transportation units, upper yoke lamination and integral upper clamp transportation units. The internal active part could be disassembled for transport into several units, comprising two complete winding assemblies, their separate lead and cleat bar components, yoke shields and other insulation parts units. The frame lead could be transported inside the oil tank and be disassembled into several frame units. The oil tank could be disassembled into upper and lower oil tank transportation units. A simulated test of the whole set of procedures has been carried out in the transformer factory for split transportation, field assembly and acceptance test. The feasibility and reliability of quality control measures has been fully verified for different transportation units. Finally, the safe and reliable transportation of different parts is realized such as oil tank, core and winding etc. The maximum transportation weight of a single part is about 70 - 80 t. Different parts could be put into special transport boxes respectively and transported filled with high purity nitrogen or dry air. Transportation parameters of different parts for UHV AC on-site assembly transformer are listed in Tab.2.17.

Table 2.17 - Transportation parameters of different parts for UHV AC on-site assembly transformer

Transportation unit		Transportation dimension (length, width and height) / m	Transportation weight / t	Note
Oil tank	Upper	11.6×5.1×4.5	75	Oil tank consisted upper and lower sections, clamp and lead transported inside oil tank
	Lower	11.6×4.3×0.6	35	
U-shaped core		5.1×4.1×3.5	80	U-shaped frame and transportation box
complete assembly winding		Φ4.3×4.2 (diameter and height)	55	complete assembly winding and transportation box
Yoke		7×0.8×2.6	16	Yoke and transportation box
Insulation part		5.5×3.2×1.5	12	Yoke shield & other insulation parts and transportation box

(1) Core Frame Transportation Unit

The special transportation box can be used to transport each U-shaped core frame which would be transported after turnover to limit the transportation height. The U-shaped core frame has related fastening devices such as pulling plates, clamping pieces etc and could be transported in the vertical or horizontal position (see Figure 2.38).

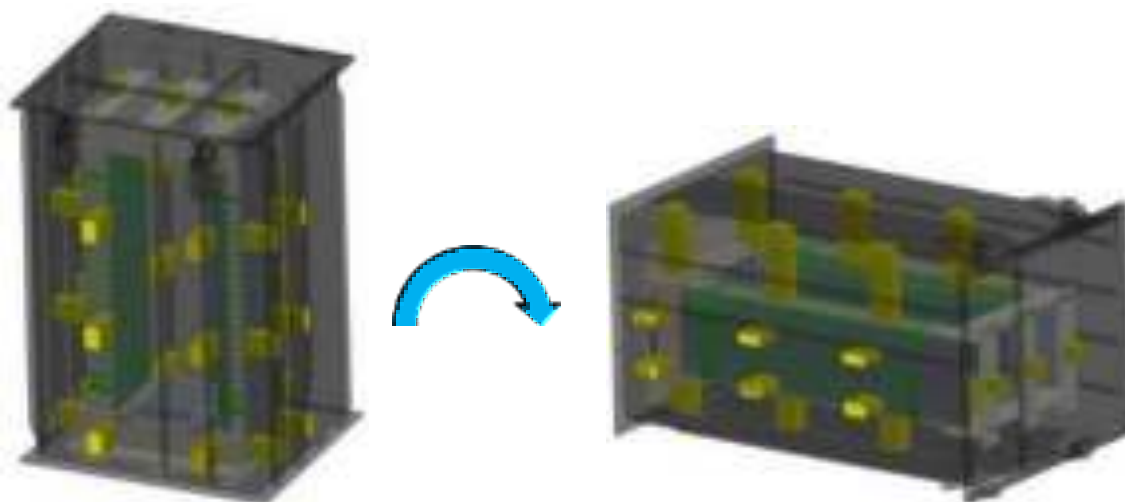


Figure 2.38 - Single transportation unit for U-shaped core frame

(2) Transportation Unit of Complete Assembly Windings

The special transportation box can be used to transport each complete assembly winding which could be transported as a unit for each column fastened by upper and lower press plates and support plates. Each complete assembled winding is transported in its own container and has an upper steel press plate installed that ensures winding pressure to guarantee transportation reliability (see Figure 2.39).



Figure 2.39 - Single transportation unit for winding column

(3) Transportation Unit of Main Tank

Temporary tank covers will be used to realize the transportation for upper and lower oil tanks respectively, including components such as insulation, leads and integral upper clamp etc. (see Figure 2.40)



(a) Transportation box for upper oil tank



(b) Transportation box for lower oil tank

Figure 2.40 - Transportation unit for main tank**(4) Other Transportation Units**

Coolers, bushings, oil pipes, oil storage tanks are transported as normal.

2.3.2.4 Field Assembly Building Design

The field assembly building can also be later used as the substation spare parts storehouse, which is shown in Figure 2.41. The field assembly building is arranged so that it has sufficient capacity to assemble one transformer at a time. To ensure a clean environment during the assembly process, an internal and external dustproof chamber is specially set up inside the assembly building. The inner dustproof chamber protects the active part during assembly by creating an environment of constant temperature, humidity and air cleanliness similar to a traditional factory environment. This can also include a mobile vacuum treatment unit, kerosene vapour phase drying equipment and other process treatment equipment. The external dustproof chamber facilitates the receiving of materials.

**Figure 2.41 - Field assembly building external and internal view****2.3.2.5 Process Quality Control Measures of Field Assembly**

Process quality control measures for field assembly mainly consist of assembly deviation control (U-shaped core frames, complete assembled windings, lead dimensions between coil limbs and core insulation resistance) and drying process. Because of variations of field environment conditions and moisture-proof measures, it is inevitable that the active part and insulation parts would gather moisture during the assembly process. Therefore, mobile kerosene vapour phase drying equipment similar to the factory has been utilized to carry out the entire drying for transformers after field assembly.

2.3.2.6 Special Acceptance Testing Methods

To meet the requirements of overall inspection and assessment of site assembled transformer performance, a special no-load and load testing system with high voltage and high current has been developed which could be used to carry out the no-load loss measurement under 100% rated voltage

and load loss measurement under 50% rated current on site. This confirms there are no defects in the core, windings and insulating materials after the process of factory disintegration, split transportation and field assembly. At the same time, combined with the induced voltage test with partial discharge measurement (IVPD), the overall inspection and assessment of transformer quality after field assembly has been successfully realized. Finally, the safety and reliability of UHV AC site assembled transformer can be guaranteed.

2.3.3 Engineering Practice of Field Assembly

The assembly process flow inside the field assembly building is presented as follows (see Figure 2.42):

Start the assembly work → Lower section tank put in position on the platform → U-shaped core frames assembly → Winding columns assembly → Upper yoke assembly → Upper clamp assembly → Leads assembly and bandaging insulation → Adjustment and press-fitting → Semi-finished product test → Finished assembly → Transportation in the substation → Installation on the foundation → Installation of external components → Vacuum pumping and oil injection → Hot oil circulating → Standing for suitable time → Acceptance test.



Figure 2.42 - Assembly process flow inside field assembly building

(1) Installation Platform Position and Assembly of Core Frames

The lower section oil tank put in position and assembly of U-shaped core frames inside the field assembly building are shown in Figure 2.43.



(a) Lower oil tank into position



(b) Assembly of No.2 U-shaped core frame



(c) Assembly sequence as No.2, No.3 & No.1 frame

Figure 2.43 - Installation platform position and assembly of first U-shaped core frame

(2) Assembly of Core Frames and Its End Product

The assembly of core frames inside the field assembly building is shown in Figure 2.44.



Figure 2.44 - Assembly of U-shaped core frames and its end product

(3) Assembly of Winding Columns

The assembly of winding columns inside field assembly building and its end product are shown in Figure 2.45.



Figure 2.45 - Assembly of winding columns and its end product

(4) Assembly of Upper Yoke and Upper Clamp

The assembly of upper yoke and upper clamp inside field assembly building as well as their end products are shown in Figure 2.46.



(a) End product of upper yoke

(b) End product of upper clamp

Figure 2.46 - End products of upper yoke and upper clamp

(5) Assembly of Leads and Semi-product Test

The assembly of leads and semi-finished product test inside field assembly building are shown in Figure 2.47.



(a) Assembly of Leads



(b) Semi-finished product test

Figure 2.47 - Assembly of leads and semi-finished product test

(6) Assembly of Final Production

The assembly of final production inside field assembly building is shown in Figure 2.48.



Figure 2.48 - Assembly of final production

(7) Drying of Production

The kerosene vapour phase drying of transformer inside field assembly building is shown in Figure 2.49.



Figure 2.49 - Kerosene vapour phase drying treatment for transformers

(8) Transportation and Installation of Transformer in Substation

The transportation in substation and installation on the concrete base of an on-site assembly transformer is shown in Figure 2.50.



Figure 2.50 - Transportation and installation in substation of on-site assembly transformer

(9) Acceptance Test

Four on-site assembly transformers have successfully passed all acceptance tests with excellent performance of various parameters. Finally, a strict review of the whole process quality has been completed for site assembled transformers after factory test, split transportation and field assembly.



Figure 2.51 - Acceptance test of on-site assembly transformer

2.3.4 System Commissioning and Trial Operation

Transformer condition is maintained by On-site inspection, protection & control, and real-time monitoring of noise, vibration, heating, dissolved gas-in-oil analysis (DGA) and ground lead current coming from the core and clamp respectively. As a result, transformers have been stable and reliable during the

system commissioning and trial operation. Finally, the first global engineering demonstration application of UHV AC site assembled transformers has succeeded.



**Figure 2.52 - UHV AC on-site assembly transformer in service
(spare phase on the right side)**

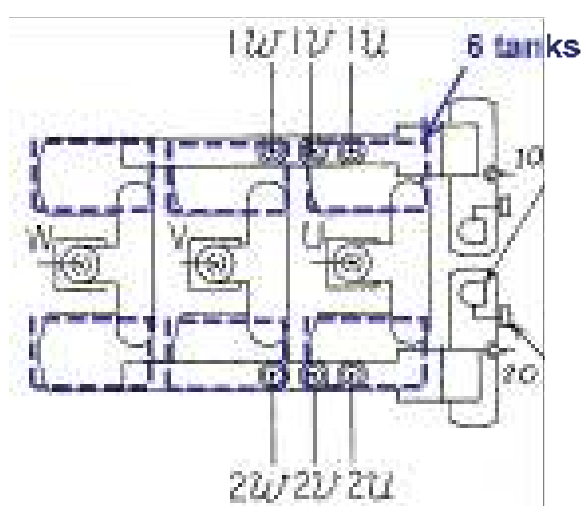
2.3.5 Conclusions

- (1) Based on key technology research and engineering, a large number of successful experiences of UHV AC site assembled transformers have been accumulated in design scheme, factory manufacturing, split transportation, field assembly, acceptance test, system commissioning and trial operation. It could be used to significantly reduce the transformer transportation weight by which the maximum transportation weight of single part is limited to about 80 t and would be a useful solution to the transportation problem of UHV AC transformers.
- (2) A series of quality control measures have been implemented to guarantee the performance of UHV AC site assembled transformers, including production quality control in the factory, transportation quality control of disassembly parts, manufacturing environment and process quality control of field assembly building etc. In particular, the application of kerosene vapour phase drying technology would be an effective solution to the assembly quality control under complicated field conditions.
- (3) Test equipment selection and development has been implemented for the requirement of site no-load and load test of transformers. Many problems have been solved such as the waveform distortion of the no-load test, the large capacity demand of the load test power and the precise control of the reactive power compensation etc. For the first time, the no-load test under high voltage and load test under large current have been carried out in the field environment same as that in the factory test to ensure the quality of UHV AC site assembled transformers after building disintegration, split transportation, field assembly and final installation on concrete foundation.
- (4) Equipment transportation is no longer an impediment and a wider geographical spread of UHV AC application is now possible. Finally, a feasible solution to UHV AC transformers transportation could be utilized in regions where transportation condition is particularly difficult or the whole transportation is rather difficult to carry out.

2.4 Split-tank type transformer

To cope with changes to the transportation conditions, the form of transformer transportation has been developed from a normal three-phase transformer to a special three-phase transformer and to a site-assembly transformer. The special three-phase transformer is a transformer in which the core and windings are divided into three for each phase and housed in a tank, and the three phase connection is made by a three phase connection upper tank or three phase connection duct. The special three phase transformer is divided into each phase tank at the time of transportation. A transportation cover (tank) is attached so that it is sealed for transportation.

In the case of transporting a special three-phase transformer to places where transportation conditions are severe such as underground substations and hydropower plants in mountainous areas, the necessity to increase the number of transformer divisions has come up. For this reason, a 6-split special three-phase transformer and a multi-split special three-phase transformer with one phase divided into two, three or greater have been produced. Examples of a 6-split special three-phase transformer are shown in Fig. 2.53 (a) (Core-form), Fig. 2.53 (b) (Shell-form), Fig. 2.54 (a) (core-form, DC 250 kV Converter station) and Fig. 2.54 (b) (Core-form, Factory substation). An example of a special nine-split special three-phase transformer is shown in Fig. 2.55 (Core-form).



(a) Case 1 - 584 MVA, Core-form

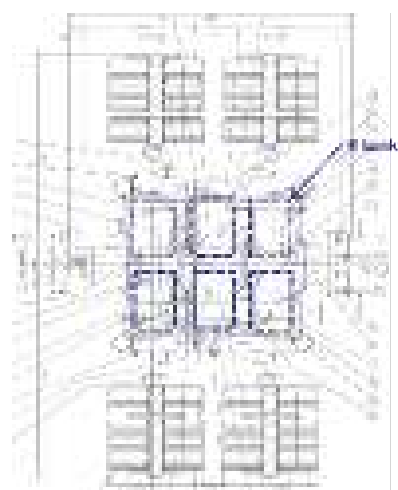


(b) Case 2 - 390 MVA, Shell-form

Figure 2.53 - 6 split-tank type transformer for pumped-storage hydraulic power plant



(a) Case 1 - 872 MVA, Core-form converter transformer



(b) Case 2 - 150 MVA, Core-form

Figure 2.54 - 6 split-tank type transformer for other cases

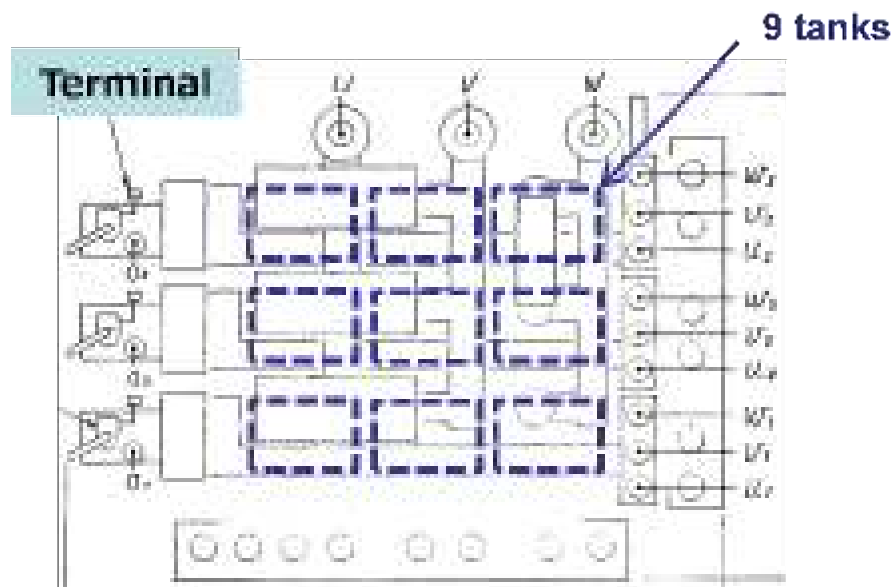


Figure 2.55 - 9 split-tank type transformer for pumped-storage hydraulic power plant (680 MVA, core-form)

3. Survey On-Site Rebuild

3.1 Experience in North America and Europe

Below are described four on-site rebuilds performed in Canada and Spain.

3.1.1 Experience A

The transformer was a 138 kV star to 13.8 kV delta transformer with a rating of 91.2/114/127.7 MVA ONAN/ONAF/ONAF and located at a hydroelectric station. This transformer failed in service due to an internal fault on the HV winding. It was decided to replace all windings and perform an on-site rebuild in the turbine hall which was in fact originally designed for un-tanking the core and windings. The turbine hall crane had the lift capacity to hoist the transformer into a pit and had the required overhead height to lift the core/windings out of the tank onto the turbine hall floor. A factory rewind was not practical due to transportation issues [9].

All new modern windings were designed and manufactured at a transformer plant. The windings were oven dried, sized, vapour phased oven dried, oil impregnated and clamped in the factory and then shipped to site in steel containers under dry air.

Prior to the on-site rebuild, the repair area in the turbine hall was thoroughly cleaned and made a limited access area to ensure cleanliness and protection of the transformer during the repair. The actual on-site rebuild work was performed by 2 factory experienced transformer technicians and supported by other workers from the hydroelectric plant. All work was inspected by a transformer design engineer at critical hold points similar to factory inspection hold points. While the windings were being replaced on the core/windings, the tank was taken to a nearby paint shop for cleaning & repainting.

After all work on the core/windings was completed, it was installed back into the transformer tank. The transformer then underwent a special drying process called Low Frequency Heating [10]. This process applies current to the HV terminals with the LV terminals shorted (similar to a factory temperature-rise test). However, the voltage is applied at a very low frequency (few mHz) so that there is negligible leakage flux (it is proportional to frequency) and also the applied voltage is very low (impedance voltage is also proportional to frequency). In this manner, the current can be applied with no oil in the tank (safe due to the low voltage) and the temperature across the winding is constant (since there is no hot spot gradient and no oil gradient). The winding temperature can then be raised to 110°C for an effective dryout. This special LFH dryout process is required for the site repair due to the long exposure of the windings during the on-site rebuild. After this LFH process was completed, a dryness of 0.3 % moisture in cellulose was achieved.

The below tests were successfully done on the transformer:

- Ratio, Resistance, SFRA, Insulation Resistance, Power Factor, Auxiliaries
- No-load Loss, Load Loss, impedance
- Applied voltage and induced voltage dielectric tests

The losses and dielectric tests were completed using a mobile test trailer.

Below are pictures that show the site repair from start to finish.



Figure 3.1 - Transformer Being Moved from Pad to Turbine Hall



Figure 3.2 - Transformer Being Moved into Turbine Hall Pit with Overhead Crane



Figure 3.3 - Core/Windings Being Removed from the Tank



Figure 3.4 - Removal of the Top Yoke of the Core



Figure 3.5 - Removal of Windings



Figure 3.6 - New Winding Shipping Containers and Installation of New Windings



Figure 3.7 - Re-installation of Top Yoke of Core and Finished Core/Windings



Figure 3.8 - Cleaned Tank, Core/Windings Back in Tank and Sealed Tank



Figure 3.9 - Assembled Transformer Undergoing Final HV Field Induced Voltage Test

3.1.2 Experience B

This transformer was a 345 kV/138 kV auto transformer with a 12.47 KV tertiary rated for 78 Mvar and a main rating of 207/272/340 MVA ONAN/ONAF/ONAF. It was removed from service due to high gassing which was later found to be due to a flashover from the tertiary winding to the core (because of earlier winding buckling). It was decided to replace all windings in an on-site rebuild due to transportation issues and better schedule.

This transformer was located in a switchyard with no available local building – thus a temporary building was constructed adjacent to the transformer. In this manner, the tank with accessories could be left on the pad and the core / windings could be lifted out of the tank into the temporary building for repair. The temporary building was constructed using large wood timbers for the flooring with a rubber floor overlay. The temporary building had a steel frame with removal roof sections to allow crane lifts. The building was sealed and had an atmospheric control to ensure clean and dry air quality in the building for the transformer. The building was cleaned (vacuumed & mopped) each night to ensure a high level of cleanliness was maintained.

New windings were designed, manufactured, vapour phased and shipped to site from a transformer factory similar to the other on site rebuild.

The core and windings were removed from the tank using a large 450 T mobile crane and placed into the temporary building for repair. The core top yoke was taken out and the old windings were removed using a boom truck crane. The new windings were installed, and the top yoke was put back in. When completed, the core/windings were placed back into the tank (which was newly painted on the pad) using the 450 T mobile crane. A Low Frequency Heating (LFH) dryout (as described up above) was also performed on this large transformer and a dryness of 0.4 % moisture in cellulose was achieved [11].

Full dielectric testing was done on the transformer including impulse tests. A special mobile test set was brought to site for the impulse tests. Another mobile test set was provided for the other tests. All testing was performed successfully.

Pictures of the on - site rebuild can be seen below.



Figure 3.10 - Original transformer in service prior to the failure



Figure 3.11 - Temporary Building Next to the Transformer Pad with Air Control



Figure 3.12 - Removal of the Cover and Removal of the Core/Windings from the Tank



Figure 3.13 - Windings Being Removed from the Core/Windings and New Windings



Figure 3.14 - Installation of New Windings and Core/Windings being worked on



Figure 3.15 - Painted Tank (done on pad) and Completed Core/Windings



Figure 3.16 - Heavy Crane Lift of Repaired Core/Windings



Figure 3.17 - Installation of Bushings, LFH Dryout (hoarding required due to cold weather)



Figure 3.18 - Impulse Testing

3.1.3 Experience C

The two transformers were 400 kV/230 kV with 500 MVA ODAF rating. The transformers received new windings, bushings, OLTC, tank and cooling. The rating was increased to 600 MVA. These were shell type transformers. The on-site rebuilds were performed in a temporary tent with removal wall panels similar to the above example of on-site rebuild.

The first transformer was dried with traditional vacuum / hot oil spray and the second unit was dried with the LFH technology, which reduced the drying time by 1 week.

The following tests were performed:

- Insulation resistance.
- Capacitance and Power Factor in windings.
- Capacitance and Power Factor in bushings.
- Ratio and vector group.
- Winding resistance.
- Excitation current at reduced voltage.
- Leakage reactance.
- Cooling equipment.
- FRA.
- DFR
- Induced overvoltage with Partial Discharge measurement.
- Applied overvoltage.
- Lightning impulse test
- No Load losses and current measurement.

Pictures of the on - site rebuild can be seen below.



Figure 3.19 - Transformer



Figure 3.20 - Temporary Building



Figure 3.21 - Shell Type Core Stacking



Figure 3.22 - Field Testing

3.1.4 Experience D

The transformer was 132 MVA, 345/55-55 kV, HVDC application and originally manufactured in 1983. The transformer failed in service requiring a full rewind.

A site building was used for the site repair. Due to height limitations, the core and windings were left on a heavy haul trailer which was moved outside as required for with mobile crane lifting. There was a heightened level of cleanliness required for the HVDC application. The windings were manufactured in a transformer factory and shipped to site in special steel containers. The transformer dryout was performed using LFH technology.

The transformer underwent AC and DC high voltage testing which required 3 separate sets of large mobile test equipment:

- Impulse Test
- Switching Surge Test
- DC Tests including Polarity Reversal Test and DC High Potential Test
- Excitation Current & No Load Loss Tests
- Impedance and Load Losses Tests
- Applied Potential (Hi-Pot) Test
- Single Phase Induced Test with PD measurement
- 15 minute over excitation Test

Several pictures are shown below of the HVDC site repair [12] .



Figure 3.23 - Transformer Un-tanking



Figure 3.24 - Transformer New Winding Installation and Cleats & Leads Work



Figure 3.25 - DC HV Testing

3.2 Experience in China

The on-site rebuild transformer was a single phase HVDC transformer that failed after a short time in operation. The failure was due to a short inside the converter winding caused by a manufacturing deviation during winding copper soldering to the winding exit lead. The transformer was a three winding type transformer 230 kV star to 208 kV star (connected to 500 kV DC converter bridge) to 208 kV delta (connected to 250 kV DC converter bridge) with a rating of 345 MVA. It was decided to perform an on-site rebuild or repair of the transformer due to transportations challenges and to accelerate the repair time of the transformer.

A hard case repair facility at site was prepared to provide a proper environment for the transformer repair including active part disassembly, re-assembly and processing. The repair facility was designed enabling the transformer to enter via railway and enabling heavy lifting inside the tent via mobile crane. The roof of the tent was especially prepared to enable opening without losing mechanical stability of the overall structure. Further the floor of the repair facility was designed according to requirements for transformer factory facility. The facility was equipped with air conditioning system to control environmental conditions during repair work and to apply a slight overpressure to avoid contamination with dust and particles from outside. Strong focus was put on environmental conditions during repair work to avoid any influence by particles and dust. Figure 3.26 shows pictures of the repair facility.



Figure 3.26 - left: Repair facility outside view with open roof top; right: Repair facility inside view with air conditioning device and heater

Before the transformer disassembly, an in-tank inspection was performed to determine the affected limb/winding of the parallel connected limbs. The main components were disassembled before transformer movement into the repair facility. The conservator, cooling plant, AC terminal bushings and turrets, the DC terminal delta bushings and turrets were all removed after draining the oil. Figure 3.27 shows the dismantling of the main components.

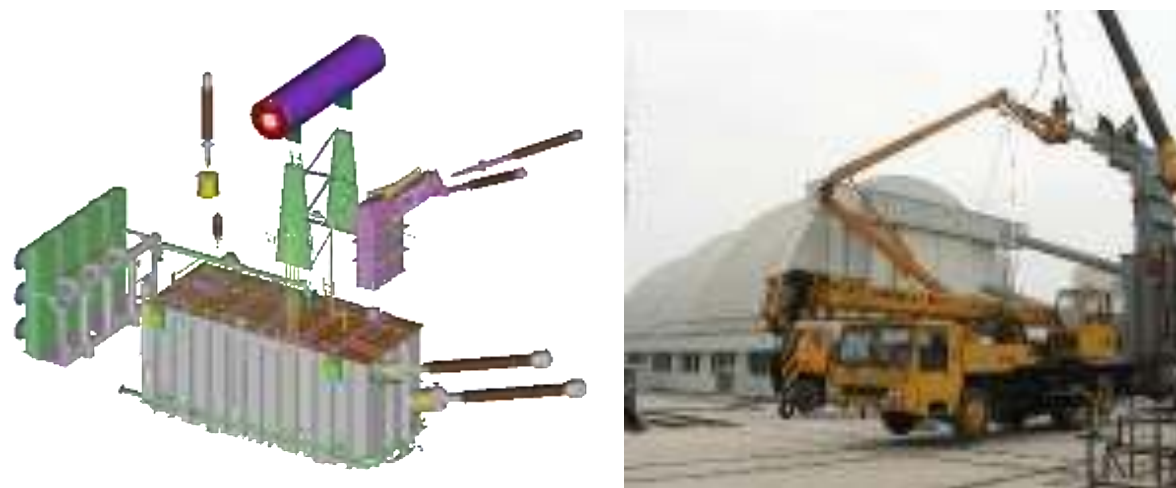


Figure 3.27 - left: Sketch of main component disassembly; right: Photo taken during disassembly of main components

The further transformer disassembly was performed inside the repair facility. The facility roof top was removed to enable lifting of heavy components such as the tank cover, clamping frame and finally the winding block. The upper yoke was removed and the leads were disconnected while the roof top was closed. The damaged winding block was removed via mobile crane and open roof top. A special lifting device was designed to lift the winding block from the core. Further special designed beams stabilized the transformer tank during disassembly at the tank opening. Figure 3.28 shows the disassembly of the transformer.

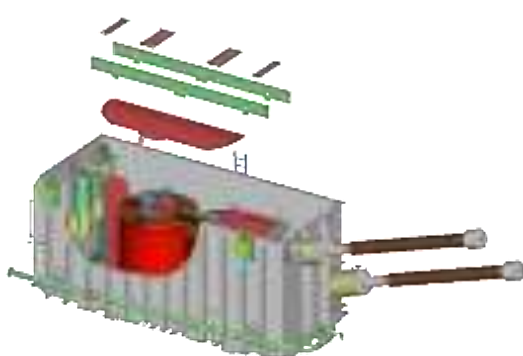


Figure 3.28 - left: Sketch of disassembly; right: Photo taken during upper clamping arrangement disassembly

A new winding block was manufactured in the transformer factory. The windings and winding block were treated in the same manner as normal factory manufactured windings (dried and oil impregnated via oil spraying immediately after the drying process was finished). The winding block had clamping forces applied to prevent height increase. A special winding block tank for shipment was designed and manufactured enabling constant clamping force to the winding block.

The winding block was replaced in one sequence. First the new winding block tank was lifted into the repair facility and the new winding block was un-tanked. Next the damaged winding block was lifted from the core and the new winding block was assembled to the core. This was all performed on a day with good weather to avoid contamination to the new winding block and the active part. Figure 3.29 shows the winding block exchange.

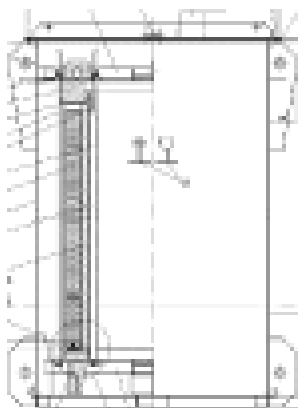


Figure 3.29 - left: Drawing of winding block shipment tank; middle: Lifting of winding block tank into repair facility; right: Removal of damaged limb while new winding block stand beside for replacement

The re-assembly was done in reversed direction:

- Yoke stacking
- Assembly of the clamping frame and retightening of the core
- Lead re-connection
- Winding block pressing
- Check of winding resistance and voltage ratio

Next the modified tank cover was assembled. The tank cover was modified with special pipes and spray nozzles on the inner side of the tank cover. These nozzles were used to clean, dry and impregnate the

active part under vacuum condition via oil spraying. The oil spraying was performed under vacuum and with an oil temperature of approximately 80°C. The moisture was extracted from oil drainage to determine the drying status. The drying process was completed after reaching a sufficient level of remaining moisture in the oil drainage. The nozzles were removed from the tank after drying finalization without lifting of tank cover. The performance of the drying process was approved via dew point measurement.

The final assembly of the transformer was done outside of the facility and the components were assembled to the transformer. Vacuum oil filling, oil filtration and vacuum were done using mobile treatment devices and per transformer factory parameters.

Acceptance testing was performed to verify the repair:

- Insulation resistance
- Capacitance and Power Factor in windings
- Capacitance and Power Factor in bushings
- Ratio and vector group
- Winding resistance
- Induced AC test of valve windings (long duration)
- Applied DC test of valve windings
- Second induced AC test of valve windings (long duration, to verify DC test results)

All tests were completed successfully.

3.3 Experience in Japan

3.3.1 Introduction

Originally, power transformers were transported as a single item (non-segmented). However, in the recent years, transportation conditions have become very severe due to the size reduction of train cars & loads and the loss of local spur rail lines. This occurred due to urbanization of the areas where substations are located in Japan. In addition, it is anticipated there will be higher demand for transformer replacement as the number of aged equipment grows. Therefore, it is expected that on-site assembly transformers will be adopted.

On the other hand, when transformer internal failures occur such as in the core or winding, it is necessary to transport them to the factory as there are limitations in dismantling or repairing locally. However, in recent years, formal railway transportation permitting has become more difficult in Japan and it is concerning that the repair time for transformers becomes too long. In addition, failure investigation and repair at the factory increases repair cost as round-trip transportation between the factory and the site is required.

As an effective measure to cope with the above challenges, on-site repair or replacement is considered to be a viable option [13] [14]. On-site refurbishments are reported to have been carried out for high voltage, large capacity transformers [15] [16] and large capacity shunt reactors [17]. In the case of those examples, large-scale clean rooms were set up at locations different from where transformers are installed. However, there are substations which do not have this kind of facility. Therefore, it is desirable to establish measures to carry out refurbishment at the location where the transformer is installed.

A single-phase pilot unit of 154/77 kV and 200/3 MVA was produced to cover the 154 kV class for which the on-site assembly transformer experience is small.

3.3.2 On-site refurbishment overview

Based on the examples of winding refurbishment, Figure 3.30 shows the conventional refurbishment process by transporting it to the factory and Figure 3.31 shows the refurbishment process utilizing the on-site assembly technology.

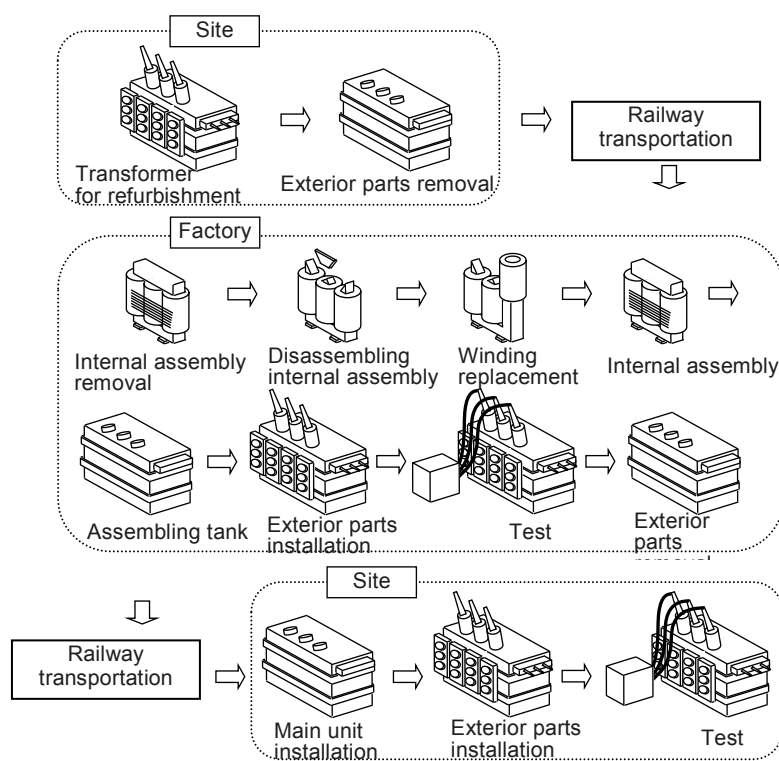


Figure 3.30 - Refurbishment process at factory

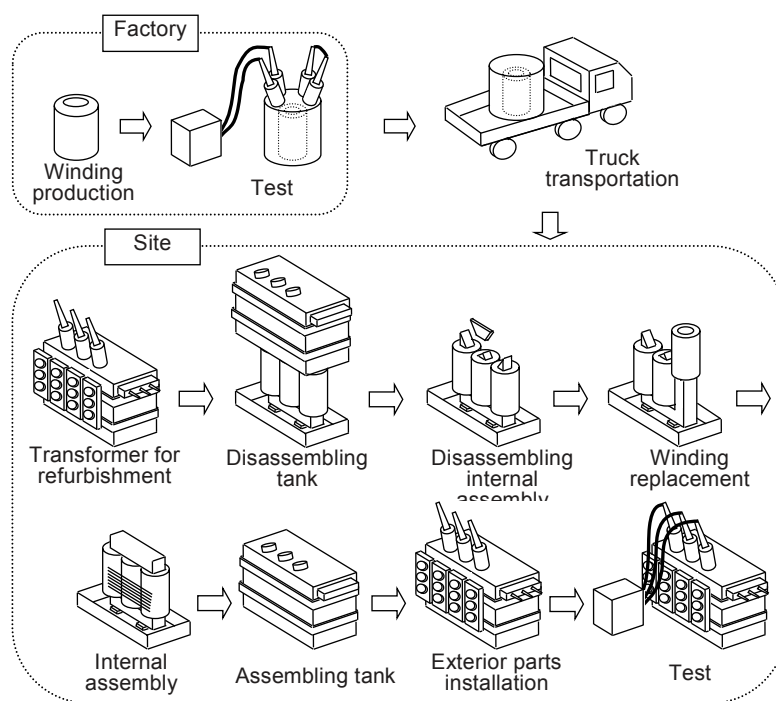


Figure 3.31 - Refurbishment process at site

3.3.3 Challenges for on-site refurbishment and study on countermeasures

(1) Transformer structure compatible with refurbishment work

When the transformer is to be refurbished at site, it is necessary to lift the internal assembly out of the transformer if the tank can only be separated at the cover. The internal assembly of 154 kV class transformers has a weight of 100 t or above requiring it to be lifted by a 200 t class crane. There are some substations where there is insufficient space to set up a crane. For these cases, the heavy lifting can only be done with 65 t cranes or less. Facing this, tank separating points are added for the lower part of the main unit tank as shown in Figure 3.32 so that it will be possible to work on the internal assembly of the transformer by lifting the tank only - which is much lighter than the internal assembly of the transformer. In addition, an inspection window for a fibre scope is provided to identify failed internal parts at the site.

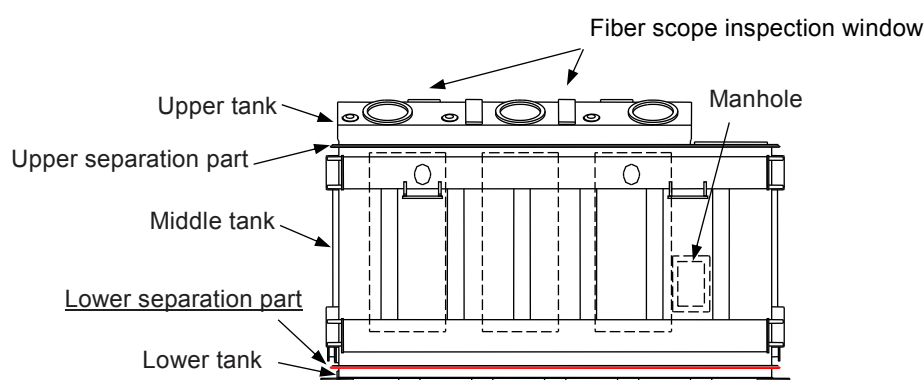


Figure 3.32 - Additional separation parts for transformer main unit tank

(2) Refurbishment procedure in view of limitation on on-site work

In the disassembly and assembly processes of transformers for the refurbishment of cores, there are operations to lay down and up right a core with dedicated equipment called the core erector as shown in Figure 3.33. Normally a 200 t class crane is required and again there are substations that cannot facilitate such a large crane. For this reason, the core rotation machine as shown in Figure 3.34 was adopted which enables core laying down and erecting operations without using a crane. This core

rotation machine facilitates core assembly work of on-site assembly transformers. The tank or structure to hold the core of the core rotation machine is designed so that it does not have to be lifted in and out. In addition, consideration is given so that it can be installed at the transformer lower tank with the anticipation that the refurbishment work is carried out at the installation location of a transformer.

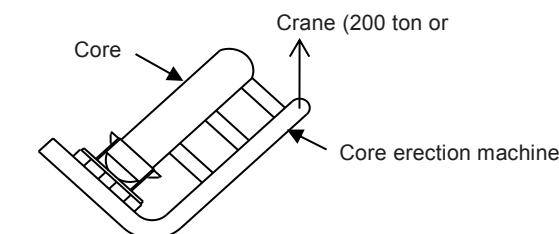


Figure 3.33 - Conventional laying down and erecting work

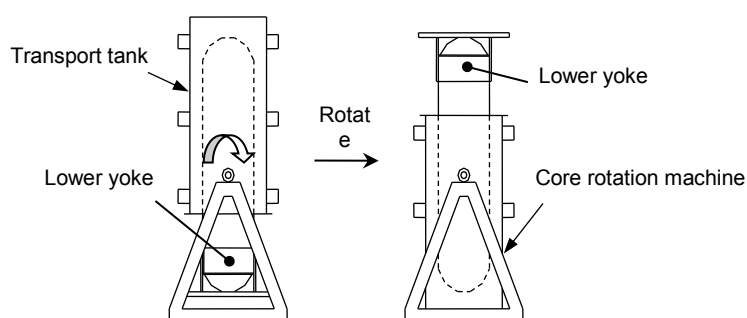


Figure 3.34 - Core rotation machine overview (Core disassembly work)

(3) Quality control

Disassembly and assembly work will be performed in the clean house where dust volume and humidity are controlled as the internal assembly of the transformer is exposed to the atmosphere at the site. However, it is anticipated that it may be necessary to refurbish at the transformer pad due to the space limitation of a substation. For this reason, the clean house is designed in such a way that it can be assembled at the transformer pad as shown in Figure 3.35.

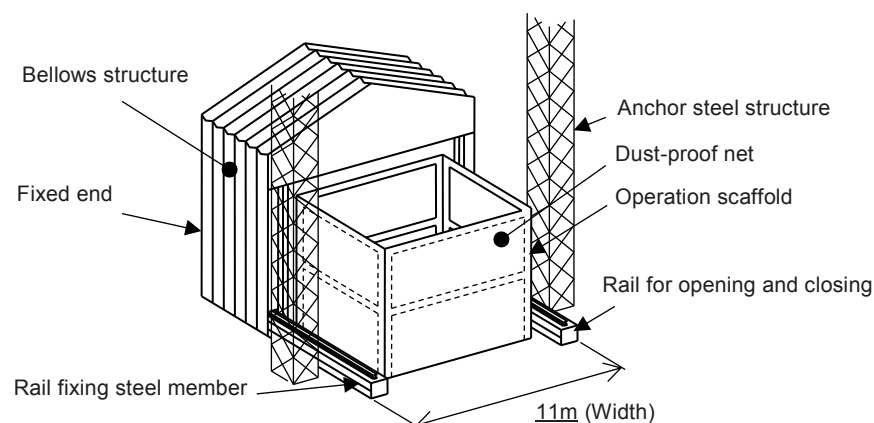


Figure 3.35 - Clean house outline view (Opened condition)

Specifically speaking, it is designed to deal with various foundation shapes by providing the fixing steel member with a rail for sliding the bellows to open and close the clean house. It also has the width which can fit when the space between anchor steel structures for the power line connections is narrow (in the case of our company, the smallest is 11m for 154 kV class transformers.)

In addition, to prevent moisture and dust from entering the clean room building, the winding is provided

with a film pack into which the dry air is blown as shown in Figure 3.36 at the time of the on-site refurbishment. It is difficult to put a bag shape film onto the winding due to lead connections. Therefore, it is designed to wrap the sheet shaped film around the winding.

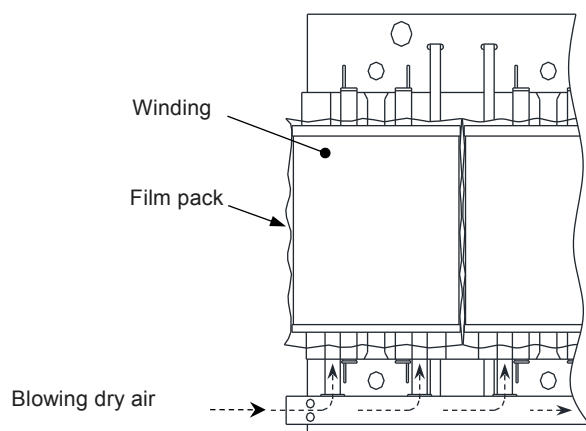


Figure 3.36 - Preventive measure for moisture and dust ingress for winding

(4) Unit test for winding performance check

In the case of repairing internal failures of transformers, the shop test for the winding needs to be performed without a real core (hereafter referred to as “air-core”), unlike a new transformer being manufactured. Since the new winding is the same design as the old winding, the main purpose of the shop test is to check the manufacturing quality. Therefore, the test items related to the winding as a unit with the air-core are in accordance with Table 3.1. Among those, it is difficult to perform the short-circuit impedance measurement with the existing technology. For this reason, the leakage inductance measurement was invented as an alternative measure noting that the component of the leakage inductance is the dominant factor with respect to the short-circuit impedance measurement. It is possible to assure the health of the winding if the calculated value of the inductance of the air-core is confirmed to coincide with the measurement value.

Table 3.1 - Main shop test items with air-core

Test item	
Winding resistance measurement	
Insulation resistance measurement	
Dielectric loss angle measurement	
Short-circuit impedance measurement (Leakage inductance measurement) ^{Note 1}	
Withstand voltage test	Voltage application test
	Induced test (Substituted by switching impulse test)
	Lightning impulse withstand voltage test

Note 1: Test item not possible with existing technology

3.3.4 Verification by pilot unit

To verify items studied in Paragraph 3, the single-phase pilot unit was produced. Figure 3.37 shows the schematic construction of the pilot unit.

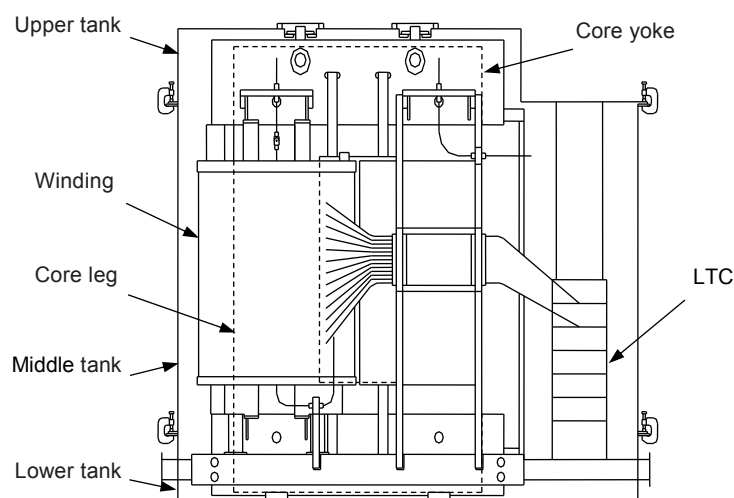


Figure 3.37 - Single-phase pilot unit schematic construction

(1) Transformer construction compatible with refurbishing work

As the transformer main unit tank is divided into 3 parts, it became possible to expose the internal assembly at the site by lifting the upper and middle tanks. This facilitates the refurbishment of the internal assembly of the transformer at the site. Figure 3.38 shows lifting of the upper and middle tanks.



Figure 3.38 - Lifting upper and middle tanks

(2) Refurbishing procedure in view of limitation on on-site work

The core refurbishment work was verified by using the core rotation machine. It was confirmed that the rotation work can be done without issue with a core being mounted. Assembly and removal of the core rotation machine are confirmed to be possible by a 65 t class crane. Further, it is confirmed that the core rotation machine can be installed on the lower tank and that the work to rotate the core in the clean house without interfering with other items is possible. Figure 3.39 shows the state of the core rotation operation.

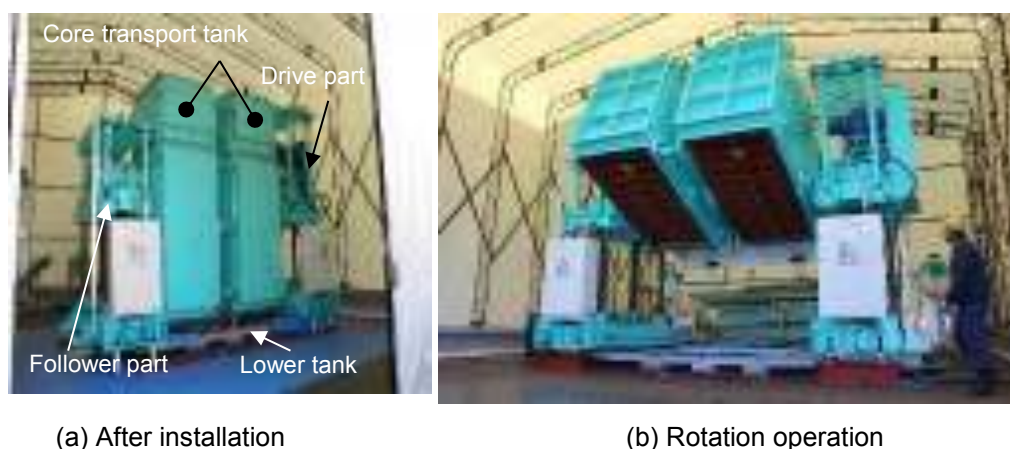


Figure 3.39 - Core rotation machine

(3) Quality control

Space where the installation was done was graded by 1 % towards the direction of the rail for opening and closing. It is confirmed that the clean house can be set up level by providing the rail fixing steel member. This indicates that it will work when the foundation shape changes depending on substations. Figure 3.40 shows the installation state of the clean house and Figure 3.41 shows the equipment layout for the on-site work.



Figure 3.40 - Clean house installation states

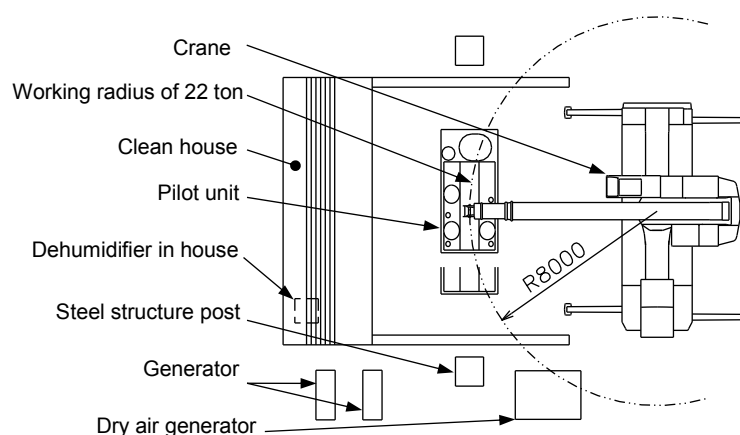


Figure 3.41 - Equipment layout for on-site work

It is confirmed that the inside of the clean house can be kept at the equivalent factory environment (humidity is 50 % or less and suspended dust volume is 20 cpm or less). In addition, it is confirmed that

the water content in the insulation material can be controlled as 2.0 % • wt. or less by providing the winding with the film pack and by blowing dry air. Figure 3.42 shows the winding refurbishment work in the clean house.



Figure 3.42 - Winding refurbishment work in clean house

(4) Unit test for winding performance check

Inductance of the winding as a unit was measured (inductance observed from the primary winding was measured by short-circuiting the secondary winding) and their comparison with the calculation values are shown in Table 3.2. Errors between the calculated values and measurement values are less than 2%. Thus, it is confirmed that there is no fabrication quality problem as verified by the inductance measurement.

Table 3.2 - Comparison between calculation value and measurement value air-core leakage inductance

tap No.	Calculation value / mH	Measurement value / mH	Error / %
1 (Lowest)	39.1	39.5	1.02
7 (Rated)	31.6	31.8	0.632
13 (Highest)	25.3	25.7	1.58

(5) On-site test

Completion test items to be carried out at the site after the winding refurbishment are shown in Table 3.3. Withstand voltage test at site is not performed based on the facts of the quality control in each process. This is similar to on-site assembly transformer technology.

Table 3.3 - On-site completion test items

No	Test item
1	Transformer ratio measurement
2	Polarity test
3	Phase displacement test
4	Insulation resistance measurement
5	Electric capacitance measurement
6	Dielectric loss angle measurement

No	Test item
7	Winding resistance
8	In-oil dissolved gas analysis
9	Electric insulation oil test

3.3.5 Advantages of on-site refurbishment

Based on the example of 154 kV voltage and 200 MVA capacity, a comparison of the costs and the timeline between the factory refurbishment and on-site refurbishment is shown in Table 3.4. In both cases of the winding and the core refurbishment, the on-site refurbishment has advantage in terms of cost and schedule.

Table 3.4 - Period and cost comparison required for refurbishment

Refurbishment location	Refurbishment component	Cost ^{Note 1} / %	Work period / month
Factory	Winding	100	15.5
	Core	90	19.0
Site	Winding	70	11.5
	Core	60	12.0

Note 1: 100% cost is based on the winding refurbishment of an integral three-phase type.

3.3.6 Conclusion

We have studied the requirements for refurbishment of transformers at their installation locations, the procedure, the quality control and the performance check tests and verified by using a pilot unit. By applying the achievements of this study, it will be possible to perform the refurbishment with less cost and shorter work period compared with the conventional method. Further, this technology will contribute to the reduction of transformer life cycle cost as this can be applied to partial renewal projects.

4. On-Site High Voltage Testing

4.1 Mobile Test Systems

4.1.1 Mobile High Voltage AC Test Systems

Past high-voltage AC tests performed on site often used motor-generator-sets, which are usually quite heavy and therefore difficult to transport [18] .

New technology was developed for a mobile AC test system, which can be integrated into a 40 ft container and uses a static frequency converter as voltage source, as shown in Figure 4.1.

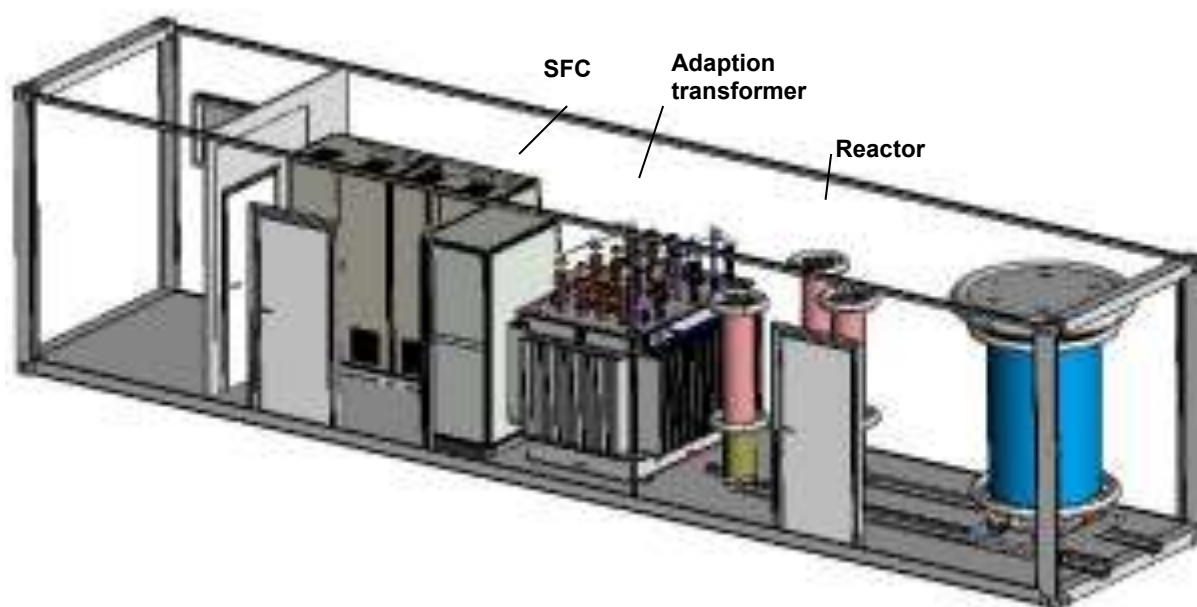


Figure 4.1 – Example of HV-AC mobile test system installed in 40 ft container

The main part of this system is the static frequency converter shown in Figure 4.2, in which the functional principle is explained. The three-phase line voltage is first rectified, thus the direct voltage is buffered by a capacitor bank. The DC voltage feeds then the inverter module, which consists of power transistors (IGBT's) and is driven by a micro-controller, thus sinusoidal modulated voltage pulses of adjustable frequency and amplitude could be generated. A controlled power sine wave filter connected to the converter output is used to filter the fundamental wave, which finally feeds a step-up transformer, which is connected to the device under test.

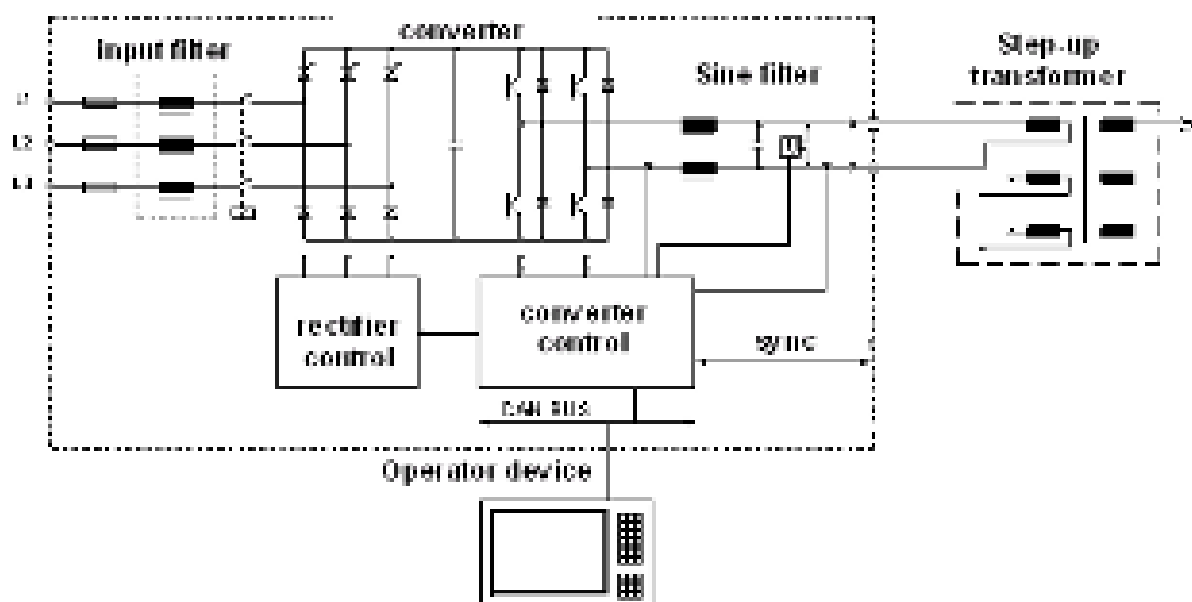


Figure 4.2 - Static Frequency Converter (SFC)

The voltages that can be measured before and after the filter are shown in Figure 4.3, thus the generation of the sine wave curves becomes clearer.

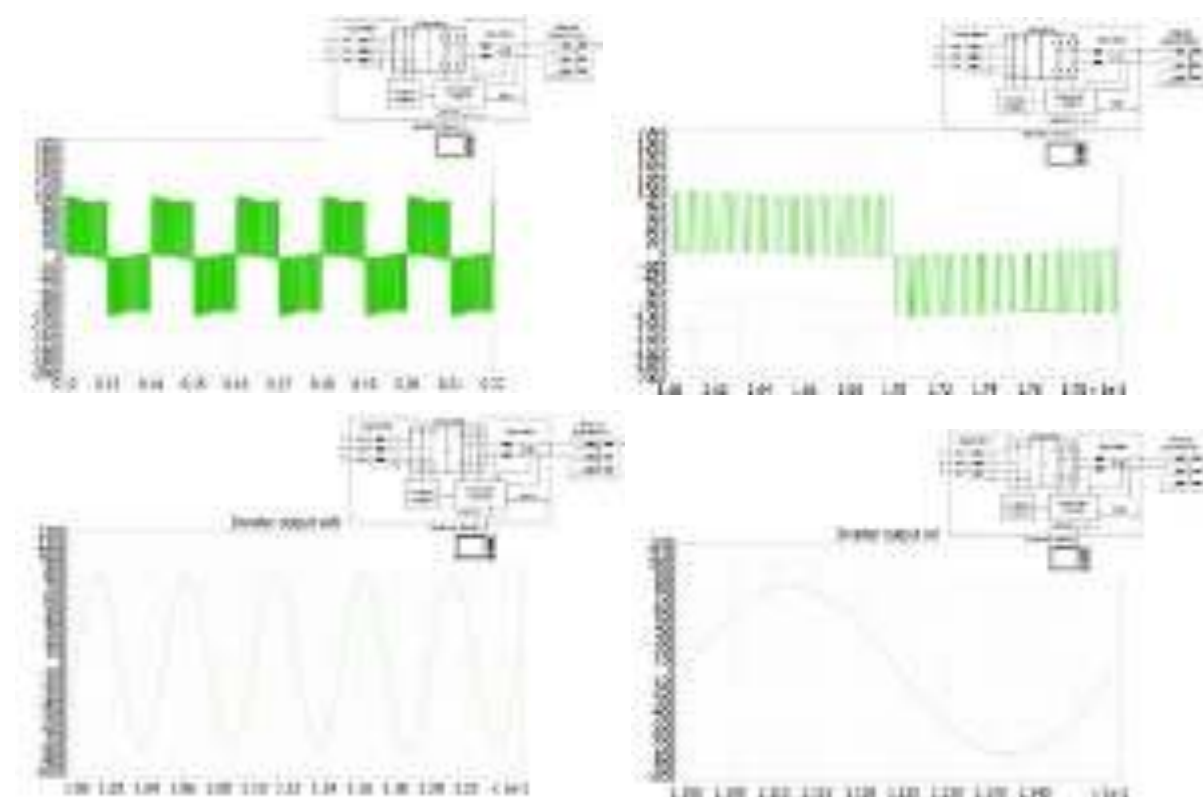


Figure 4.3 - Voltage signals measured before (above) and after (below) the filter

The applied high voltage test can be done in a resonant circuit consisting of the internal reactor as inductance and the transformer to be tested as capacitance as shown in Figure 4.4. These two components define a certain resonant frequency, which is usually automatically detected and chosen by the control of the static frequency converter. A high voltage divider in parallel to the transformer under test directly connected to the reactor is used to measure the applied test voltage.

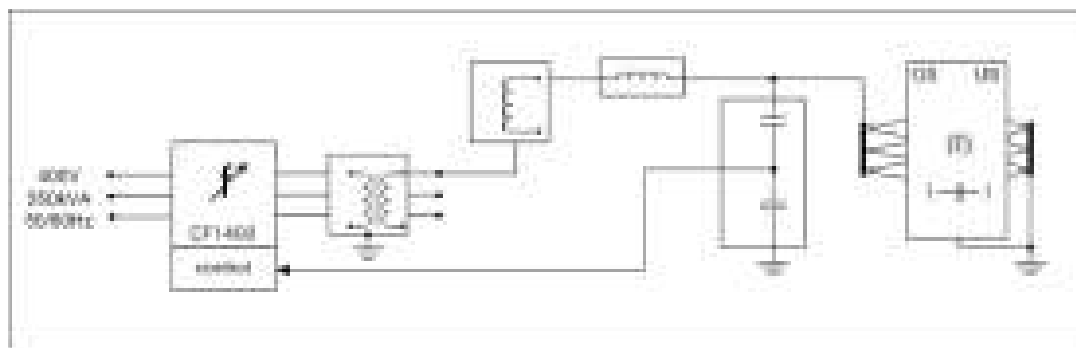


Figure 4.4 - Applied voltage test using resonant circuit

For the induced voltage test, a frequency in accordance with IEC 60076-3 is used which is adjusted to the self-compensation frequency of the transformer to be tested.

Self-compensation appears at the change-over of the test object from an inductive characteristic at lower frequencies to a capacitive characteristic at higher frequencies. At the self-compensation point, only active losses have to be fed to the test circuit and the power of the frequency converter can be kept as low as necessary. The free adjustable frequency of the system in a range from 15 to 200 Hz in 0.1 Hz steps is an important advantage in this case.

Additional inductive (for higher frequencies) or capacitive (for nominal frequency) compensation before the step-up transformer is possible. An HV T-filter at the output of the adaptation transformer serves as a partial discharge (PD) filter as well as a capacitive HV divider and an optic current measurement system to measure the voltage and current at the transformer under test precisely.

The electrical PD measurement has to be performed at the secondary site of the transformer under test using the measuring taps at the HV-bushings or separate capacitive coupling capacitors.

To perform HV tests on transformers up to a few 100 MVA, the system needs to have at least a converter power of 1350 kW in single and three phase mode and an adaption transformer of up to 2 MVA with 90 kV output - thus induced tests can be done up to 90 kV with a total harmonic distortion typically below 2 %. Applied voltage test are possible up to 500 kV using a reactor for the resonance test. For more power demand, a system can be connected in parallel increasing the total output power.

A typical control of the mobile HV-AC test system is shown in Figure 4.5, in which the touch screen panel of the control PC could be seen in the middle, whereas the PD recording system is running on the PC below the control panel.



Figure 4.5 - Control panel

All types and brands of transformers, from small grid transformers up to the largest step-up generator transformers can be tested on-site using this mobile technology. Some examples are shown in Figure 4.6.



Figure 4.6 - Examples of AC tests on-site

The partial discharge measurement during the induced voltage test is usually performed using equipment with an integrated spectrum analyser to increase the sensitivity, thus often a noise level below 50 pC can be reached. A typical PD-measurement during an induced voltage test on a three phase 420 kV transformer can be seen in Figure 4.7. It becomes obvious that in this case on all high voltage phases, only noise signals in a range of approximately 100 pC could be determined using conventional technique, which can be reduced to less than a third if additional spectrum analyser techniques are used. The sine wave acquired via the HV-bushing taps shows a low THD (Total Harmonic Distortion) at a line to line test voltage close to 600 kV.

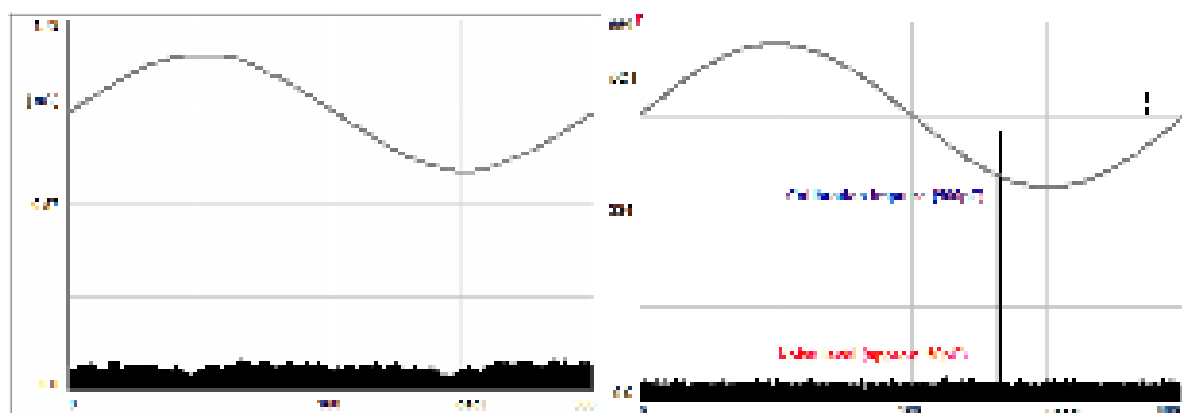


Figure 4.7 - Noise level using conventional technique

The calibration using a spectrum analyser technique is shown in Figure 4.8, in which 200 pC is used as the calibration charge, thus centre frequencies below 1 MHz according to IEC standards can be found, with a noise level in a range of 20 to 30 pC. Depending on the test environment, the impact of the external noises can vary between 10 to 500 pC (in some extreme conditions – industrial external noises can rise up to nC).

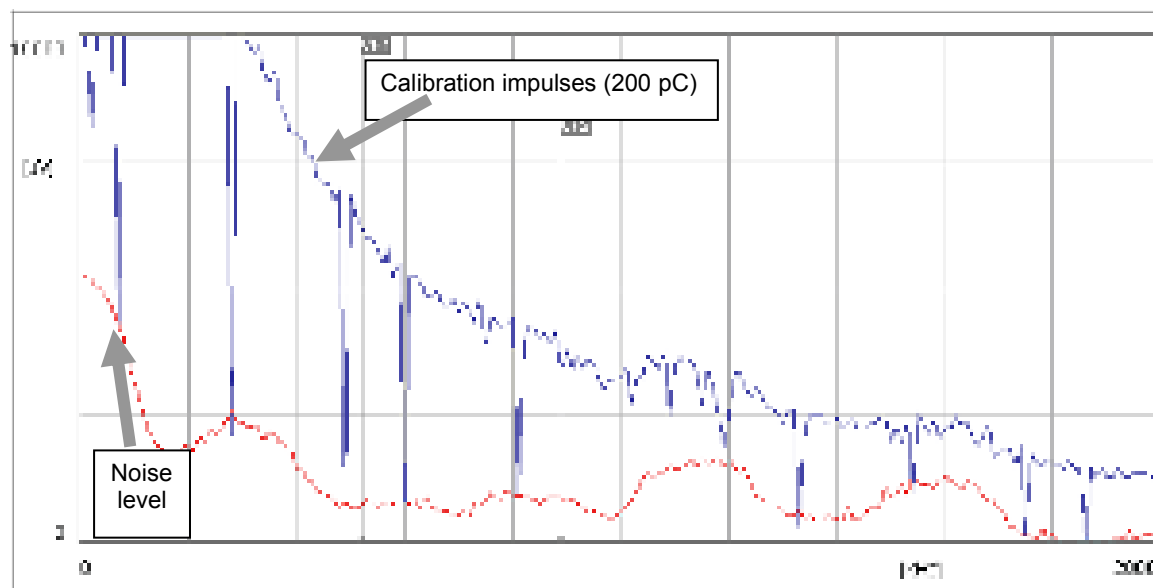


Figure 4.8 - Noise level using spectrum analyser technique

If load losses or temperature-rise tests need to be performed, additional containers with capacitive compensation up to 200 Mvar are available today as shown in Figure 4.9. Thus today there is almost no restrictions concerning AC tests.



Figure 4.9 - Additional external capacitive compensation for temperature-rise tests

However, if more active power is needed, mobile AC tests systems can be operated in parallel. Up to 8 modules have been used parallel to achieve $8 \times 1\,350\text{ kW}$, which is equal to approximately 10 MW. Figure 4.10 shows an example of a test with 2 mobile test systems running in parallel.



Figure 4.10 - AC test with 2 mobile test systems in parallel

4.1.2 Mobile Impulse Test Systems

Impulse voltage tests should also be performed after a repair on-site, thus mobile lightning impulse generator systems are available up to a charging voltage of 2 MV and an energy of 300 kJ. Using such systems, lightning impulse tests up to 1 800 kV and switching impulse tests up to 1 300 kV can be performed by this technique. They are installed in a 40 ft container, in which the Marx-Impulse Generator is transported horizontally. Therefore, the roof of the container must be opened before the impulse generator can be raised using a hydraulic system. This procedure can be done automatically in less than 1 hour with almost no physical labour required.

Figure 4.11 is visualizing the set-up, whereas in Figure 4.12 the system ready to use is shown.



Figure 4.11 - Set-up of system



Figure 4.12 - Mobile Impulse System

The voltage divider needed for the test is stored together with the generator. To provide a proper distance to the divider, a telescopic system is used. Thus neither a crane nor special tools are needed for the erection of such a system. This can also be used to test HV-cables, which represent a much higher capacitive load than transformers.

Below a test is demonstrated for an 850 MVA 400 kV GSU in a power plant.



Figure 4.13 - Test of an 850 MVA GSU

4.2 Experience

4.2.1 Experience A

(1) Project Outline

The transformer was manufactured in 1974. In 2016 an on-site rebuild with new windings was done for an MVA upgrade

(2) Transformer Rating

- Transformer type: Three Phase Autotransformer
- Rated Power: 600 MVA
- Rated Voltage HV: 400 kV
- Rated Voltage LV: 100 kV
- Cooling system: ONAF
- Vector group: YNa0d11
- Frequency: 50 Hz
- Year of manufacturing: 1974
- Year of re-manufacturing: 2016

(3) Purpose of the on-site high-voltage testing

On-site testing was performed for verification of the conducted work. High voltage testing equivalent to the FAT was performed for quality assurance.

(4) High Voltage Tests Performed

Each winding was impulse tested three times at 100 %. The impulse waveform was characterized by a front time $T_1 = 1,2 \mu s$ and tail time $T_2 = 50 \mu s$.

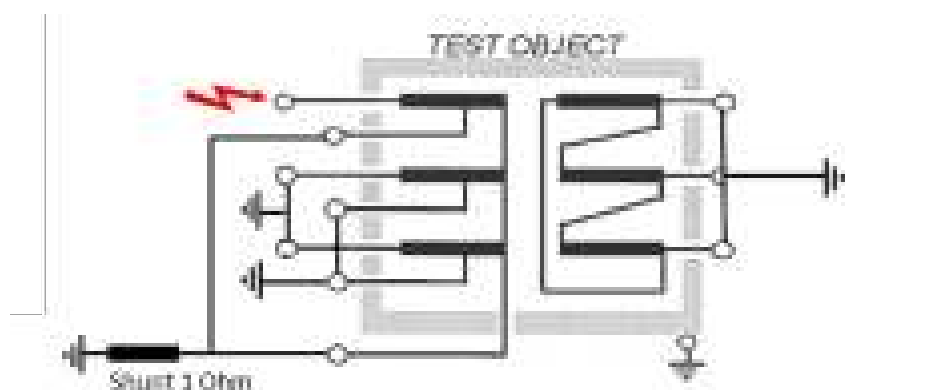


Figure 4.14 - The schemes shown general test set-up of winding connections in HV winding

An applied voltage test with a test level of 100 % of the original values (70 kV) was done on all winding successfully. The test duration was 1 minute.

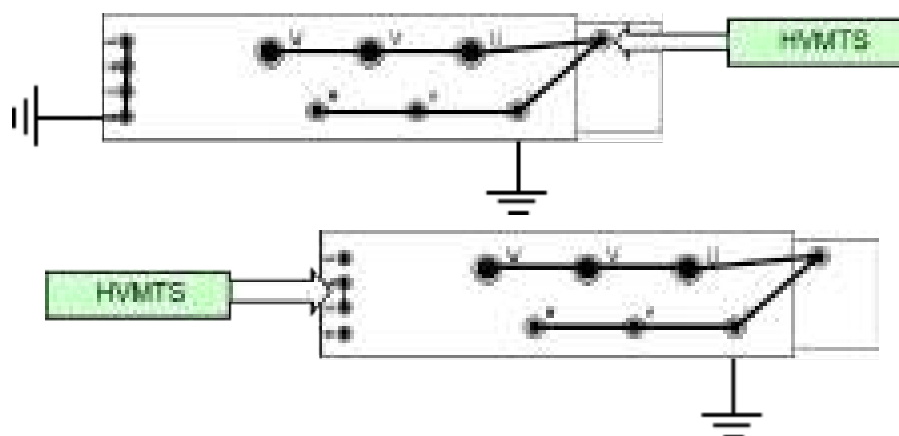


Figure 4.15 - Applied voltage test setup

The transformer passed an induced voltage test with $1.3 \times U_n$ (nominal voltage) and with PD measurement. For the 3 phases induced voltage test, the low voltage winding of the transformer under test was directly connected to the adaption transformer via the HV-divider, whereas the high voltage terminals were open and the neutral grounded. The three-phase test setup is shown in the scheme below in Figure 4.16.

The scheme also shows the functional principle of the performed PD-measurement, for which the measurement taps of the bushing (U, V, W, u, v, w) was used for the decoupling of the PD-signals simultaneously. Testing was performed continuously. No PD abnormalities in the transformer were detected by means of PD-pattern and frequency spectrum during the test time and no voltage breakdown was detected.

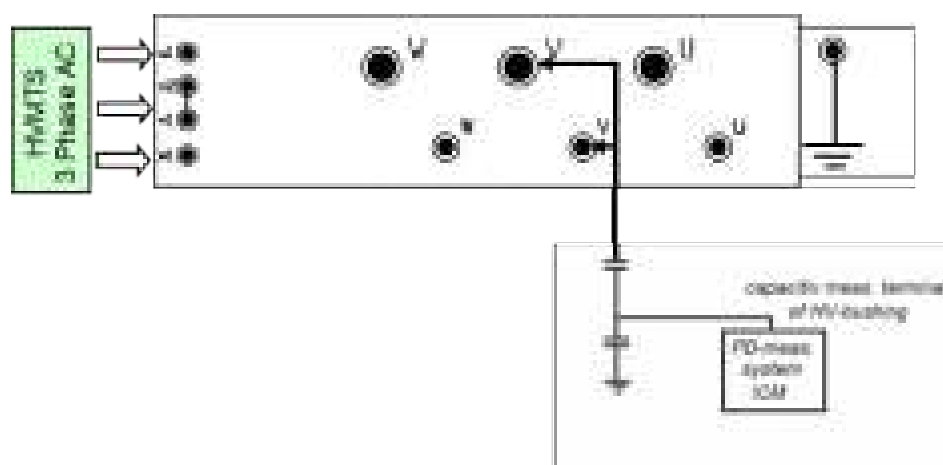


Figure 4.16 - Induced voltage test with PD measurement

The spectrum analyser method was used for the PD-measurement as a narrowband filter to optimize the signal to noise ratio. The calibration is shown in the figure below, in which a calibration impulse of 500pC was injected on the high voltage side. The background noise was the averaged measured pC on the high voltage side.

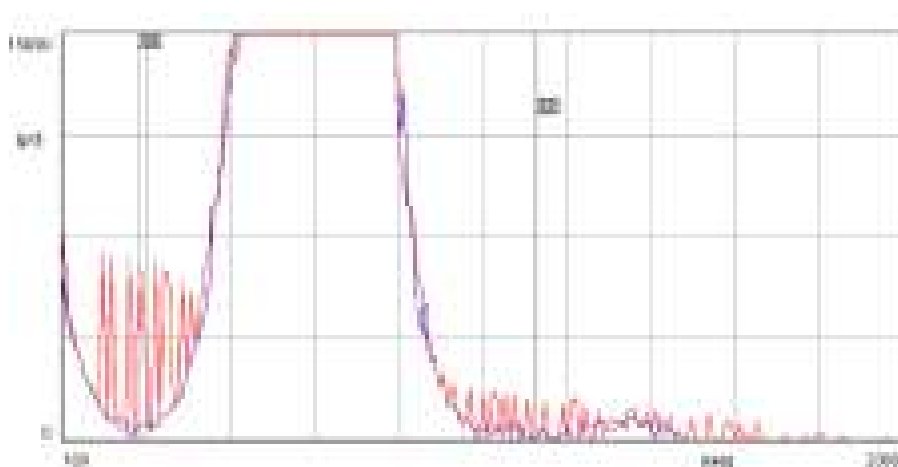


Figure 4.17 - PD measurement - calibration

Table 4.1 - Test sequences levels according to 420 kV tap-changer position 1

Test sequence	Duration	Test voltage	Voltage at HV side [kV]	Voltage at LV side [kV]
1	5 min	1.1 Ur	462	29.5
2	36 min	1.3 Ur	546	34.8
3	5 min	1.1 Ur	462	29.5

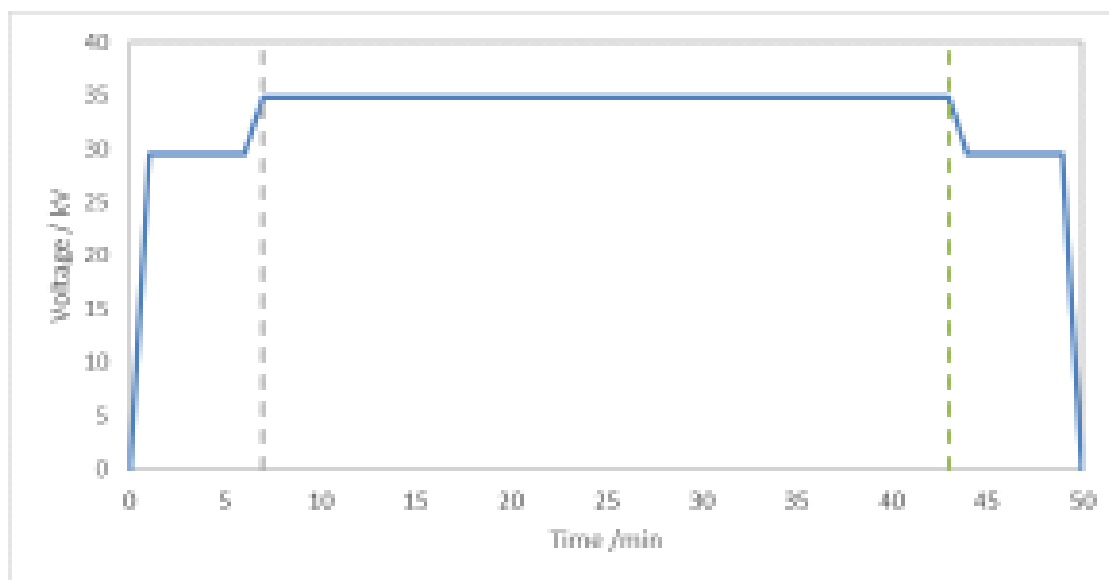


Figure 4.18 - Test sequence (Time and voltage at LV side)

During the induced voltage test, the PD-measurement was performed continuously to control any tendencies, but according to the standards, the values of the measured PD-signals were evaluated after defined durations.

Table 4.2 - PD level during test sequence 3

Voltage level	Average partial discharges [pC]		
	U	V	W
1.1 x Ur	75	75	75

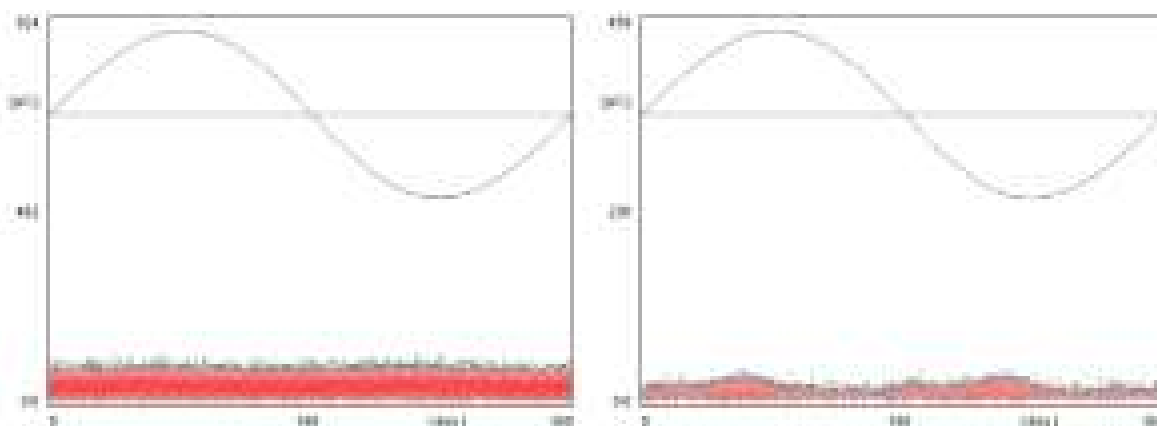


Figure 4.19 - PD Pattern recorded during test (Example)

Due to inductive power consumption of the tested object, which influences the THD of the applied sin wave voltage, the No-Load measurement was performed also at a frequency different than 50 Hz. This gives a possibility to correct this value to the 50 Hz.

(5) Specification of the facilities for the on-site high-voltage testing for this transformer.

The High Voltage Mobile Impulse Test System is installed in one 40ft. container. The functional principle of the HV Mobile Impulse Test System is based on a Marx-Generator, which is transported horizontally and can be raised by a hydraulic jacking system (see Section 4.1.2).



Figure 4.20 - LI impulse generator

The High Voltage Mobile Test System is installed in one 40 ft. Container, which is schematically shown in the Figure below and ensures an efficient transportation either by truck or by ship. The functional principle of the HV Mobile Test System is based on a static frequency converter, which converts a 400 V input voltage at 50 or 60 Hz to an output voltage with a frequency between 15 and 200 Hz. By applying

the test voltage to the secondary side of the test object, the transformer to be tested is a simple capacitive load. Therefore, an oscillating circuit can form between the test object as a capacitive load and a reactor with fixed inductance of approximately 400 H. By tuning the frequency of the converter's output voltage, the transformer to be tested and the reactor are operated in resonance, thus the converter only must cover the losses of this resonant circuit.

Table 4.3 - Equipment of the High Voltage Mobile Test System used during testing

Equipment for Voltage Generation	Type	
	Static Frequency Converter (SFC) with integrated PD filters: Power = 1 350 kW Input Voltage = 400 VAC (diesel generator or line connection), Input Frequency 50-60 Hz, Output Voltage = 360 VAC, Output Frequency = 15 Hz – 200 Hz	
	Compensation System: Capacitive = 1 MVA, Inductive = 450 kVA	
	Step-Up Transformer: Connection group = IIIIII0, Output Voltage = 90.1 kV Total Power = 2 MVA	
	HV Reactor (Applied Voltage Test): Inductance = 400 H, Output Voltage = 500 kV, Output Current = 4 – 6 A	
HV- Filters with integrated Voltage and Current Dividers	Type	Calibration
	HV-Filter, current and voltage measuring system	YES
	3 x 100 KV, Full power range	
External Voltage Divider 500 KV	Type	Calibration
	HV Divider 500 kV operate with HV Reactor	YES
Measuring Equipment	Type	Calibration
	Power Analyzer, Minimum - 4 Channels	YES
	Partial Discharge Measurement System: - Calibration Generator - Quadrupole (Signal decoupling with separate channels Pre-Amplifier for PD and Synchronization for Voltage measurement) - Evaluation, Storage and Visualization (phase resolved partial discharge - PRPD)	YES (Calibration Generator)

The induced voltage test can be performed up to a voltage of 90 kV either in a one, two or three phase connection with a nominal power of the adaption transformer of 2 MVA, which can be overload for a short time duration.

For the connection between the HV Mobile Test System and the transformer under test, special polyethylene cables are used which are partial discharge free up to a voltage of 100 kV phase to phase or 60 kV phase to ground.



Figure 4.21 - Mobile test system used for applied and induced voltage test

(6) Transportation of the on-site high-voltage testing facilities to the site

The test equipment is stored in 40 feet container and transported by road. The container remains on the trailer during the tests.

(7) Monitoring performed

DGA sampling before and after test was performed. During AC test, PD measurement was performed.

(8) Other comments

The transformer was located on the concrete platform in the substation and was used before as a foundation for a temporary workshop..

4.2.2 Experience B

(1) Project Outline

The transformer was manufactured in 1999. A repair of the transformer was performed in 2016. Some components of the active part were replaced.

(2) Transformer Rating

- Transformer type: Three Phase Transformer
- Rated Power: 190 MVA
- Rated Voltage HV: 230 kV
- Rated Voltage LV: 15.75 kV
- Cooling system: ONAF
- Vector group: YNd1
- Frequency: 50 Hz
- Year of manufacturing: 1999
- Year of remanufacturing: 2016

(3) Purpose of the on-site high-voltage testing

After the repair, an induced voltage test with PD measurement (quality check) and short-circuit-impedance measurement were performed. The partial discharges signals were decoupled on the measuring taps of the high voltage bushings (U, V, W). The HV tests were performed in the power plant.

(4) High voltage testing performed

An Induced voltage test was performed for 60 minutes and at $1.1 \times U_n$ (nominal voltage). The maximum induced voltage on the high voltage bushing during a 40 second increase on tap changer position 1 was 299 kV. During the whole test, the voltage and current remained stable. The test was performed as agreed upon with the customer.

PD measurement was performed continuously on the high voltage side. No PD abnormalities in the transformer were detected by means of PD-pattern and frequency spectrum during the test time.

Due to the sharp edges and the short distance to the installed oil expansion vessel, external discharges (corona) occurred by $1.2 \times U_n$ on phase W. The influence of corona can be seen at the pattern on phase W.

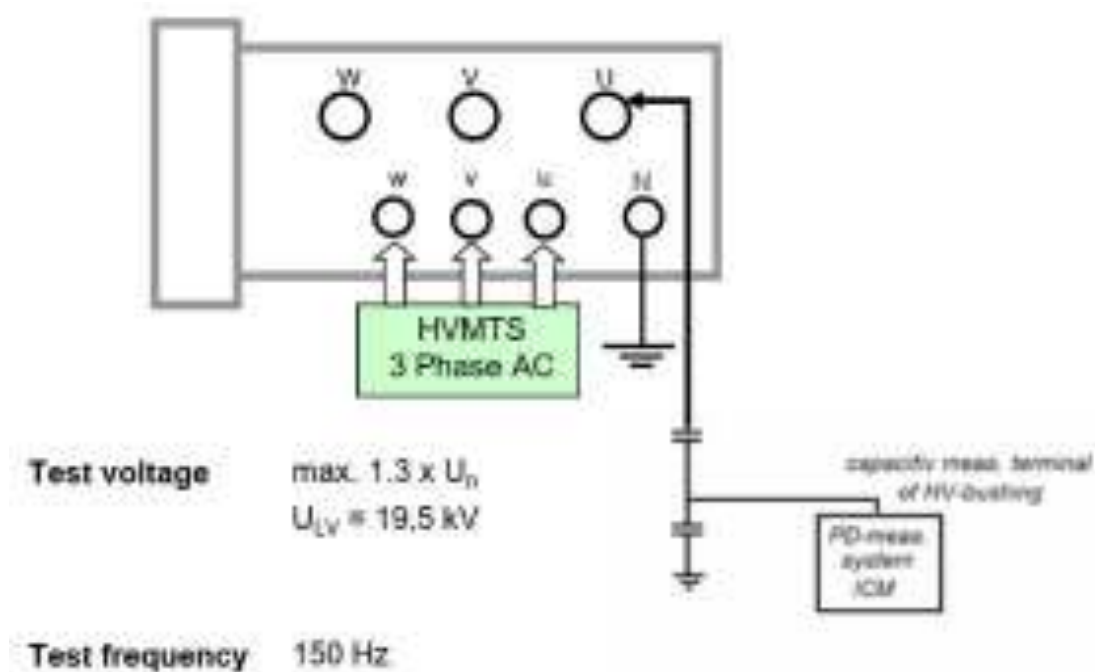


Figure 4.22 - The schemes shown general test set-up of winding connections

During the induced voltage test, the PD-measurement was performed continuously to control any tendencies, but according to standards, the values of the measured PD-signals were evaluated after defined durations.

U_r = rated voltage at maximal tap position (position 1) = 241,5 kV

U_n = nominal voltage at nominal tap changer position (position 3) 230 kV

Table 4.4 - Test sequences levels

Test sequence	Duration	Test voltage	Voltage at HV side [kV]	Voltage at LV side [kV]
1	5 min	0.2 Ur	48.3	3.15
2	5 min	0.5 Ur	120.75	7.785
3	5 min	0.8 Ur	193.2	12.6
4	5 min	1.0 Ur	241.5	15.75
5	5 min	1.1 Ur	253	16.5
6	5 min	1.2 Ur	276	18
7	40 sec	1.3 Ur	299	19.5
8	5 min	1.2 Ur	276	18
9	60 min	1.1 Ur	253	16.5
10	5 min	1.0 Ur	241.5	15.75

The spectrum analyser method was used for the PD-measurement as a narrowband filter to optimize the signal to noise ratio, however it was not possible to reduce the noise level below 220 pC at rated voltage. During the induced voltage test, the PD-measurement was performed continuously to control any tendencies. Corona discharges were observed and detected on the phase W (sharp edges of the installed oil expansion vessel).

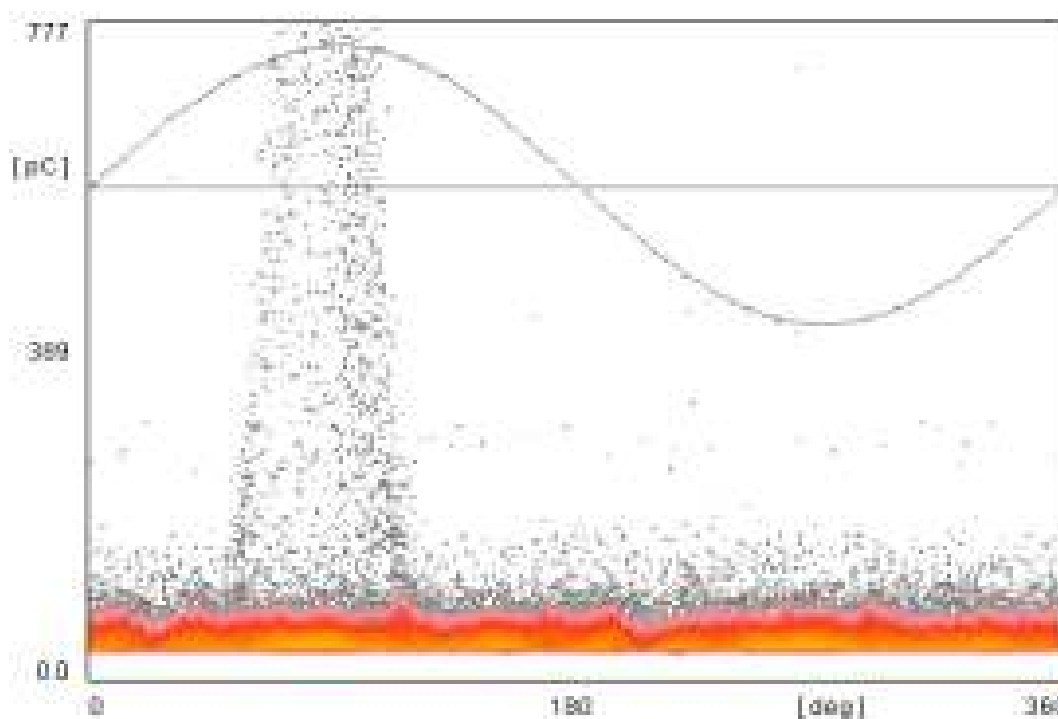


Figure 4.23 - PD Pattern recorded during test

(5) Specification of the facilities for the on-site high-voltage testing for this transformer.

The High Voltage Mobile Test System is installed in one 40 ft. Container



Figure 4.24 - AC mobile test system used for applied and induced voltage test

(6) Transportation of the on-site high-voltage testing facilities to the site

The test equipment is stored in a 40 feet container transportation and had sea / road transportation. The container was positioned on the ground due to the close proximity of an overhead line. A special loader lift truck was used to avoid crane operation.

(7) Monitoring during testing

DGA sampling before and after test was performed.

During the AC test, PD measurement was performed.

(8) Other comments

The transformer was located on the spare transformer platform in the power plant.

4.2.3 Experience C

(1) Project Outline

The transformer was manufactured in 2015. An additional temperature-rise test was performed by mobile test units as the factory test laboratory was occupied. The power demand necessary for the test was larger than a single test system. The flexible configuration allows to increase the power by parallel connection of two mobile test systems.

(2) Purpose of the on-site high-voltage testing applying

Congestion in the factory test room

(3) High voltage tests performed

A temperature rise test was performed with the below mobile test set configuration.

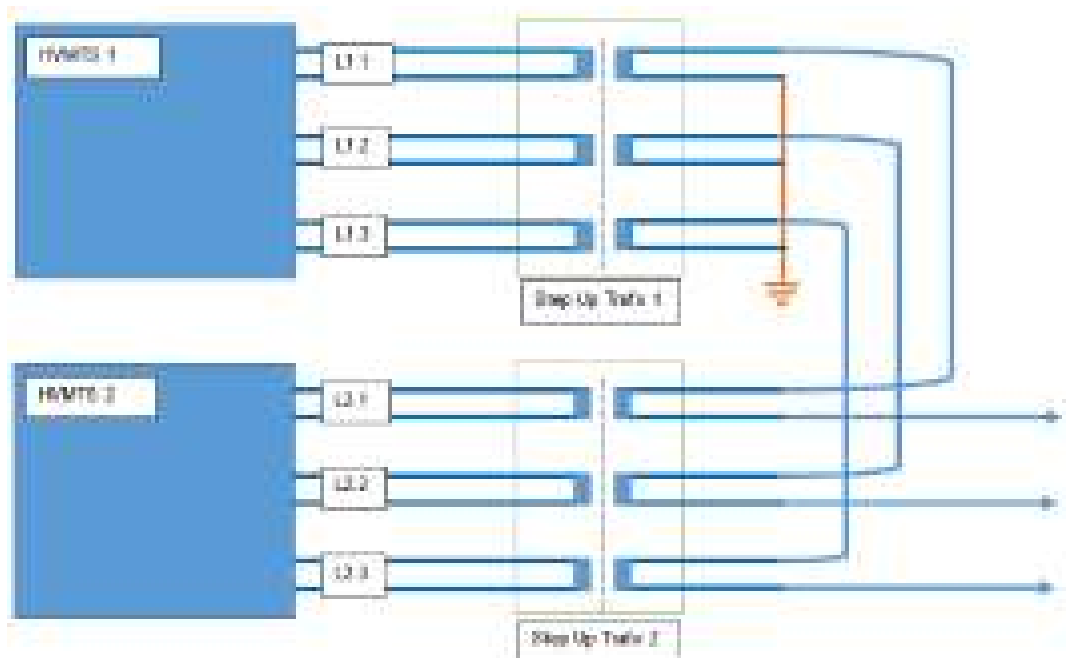


Figure 4.25 - The schemes for general test set-up of winding connections

- (4) Specification of the facilities for the on-site high-voltage testing for this transformer.
Two High Voltage Mobile Test Systems with each installed in one 40 ft. container.



Figure 4.26 - AC mobile test system used for temperature-rise test shown in front of the compensation unit



Figure 4.27 - Two AC mobile test systems used for temperature-rise test shown in front of the compensation unit



Figure 4.28 - Temporary housing for the test system - protection from the weather condition

(5) Transportation of the on-site high-voltage testing facilities to the site

The test equipment was stored in 40 feet containers with sea / road transportation. The containers were positioned on the trailer close to the temporary compensation unit.

(6) Monitoring during testing

DGA sampling before and after test was performed.

(7) Other comments

The transformer was located on the transformer platform at the manufacturing site.

5. Quality Assurance

5.1 Introduction

As shown in Table 5.1, on-site-assembled transformers are controlled so that factory assembly quality is maintained from factory disassembly to site assembly. To prevent moisture absorption of the insulation, a film pack is attached from the factory to the on-site assembling, and a clean house is installed to ensure a working environment equivalent to that of the factory for humidity and particle control. To verify insulation moisture absorption during transportation and site work, a moisture absorption monitoring material is attached at the factory so that the absorbed moisture can be checked at each process step. Detailed quality assurance at each process is described below.

Table 5.1 - Major quality assurance items for on-site assembly transformers

No	Major Item	Contents (Recommended)
1	Disassembling at factory	• Visual inspection of windings, core, lead connector and parts of internal activity • Number of parts checked
2	Transportation	• Tank internal pressure check • Impact and acceleration
3	Environment at site	• Humidity and dust in the clean house
4	Moisture absorption in Insulation materials	• Prevention from moisture absorption using coil film packing • Prevention from moisture absorption by dry air flowing • Moisture content measuring by monitoring insulation materials
5	Foreign particle and damage	• Dust proof protective covering and visual inspection
6	Check of assembly transformer	• Internal activity inspection and on-site acceptance tests

These recommended control criteria are practiced by most manufacturers with some minor differences.

5.2 Disassemble after FAT and Delivery from Factory

After the factory acceptance test (FAT), disassembling of the parts into the transportation units is carried out. This includes internal disconnections inside the tank, disassembling of the internal leads, the core and the windings. Internal lifting activities from the main tank are carried out in an air-conditioned room to prevent moisture absorption.

Items are packaged and secured within the transportation tank with a sealed positive dry air pressure to minimize deterioration in quality due to damage or moisture absorption during transportation. The windings are fitted with test insulation blocks to monitor moisture absorption between factory disassembly to transportation and site assembly. The windings are sealed in dry air and covered with a film pack.

Detailed control criteria are shown below in Table 5.2 for factory dismantling.

Table 5.2 - Quality assurance details (Disassemble and delivery after FAT)

Major item			Work item	Management item	Example of criteria
1	Oil drain	1-1	Oil drain	• Residual oil check (visual check)	No residual oil
2	Dry air filling	2-1	Dry air filling	• Dry air dew point	- 30°C or less
3	External parts disassembly	3-1	External parts disassembly	• Visual inspection • Foreign particle check	No abnormality No abnormality
		3-2	Bushing lead disconnection	• Visual inspection • Foreign particle check	No abnormality No abnormality
		3-3	Packing	• Visual inspection • Number of external parts and bushing leads	No abnormality No missing
		3-4	Dry air substitution	• Dry air dew point • Internal pressure	- 30°C or less Positive pressure
		3-5	Inspection before shipment	• Visual inspection • Number of external parts and bushing leads • Internal pressure	No abnormality No missing Positive pressure
4	Tank disassembly	4-1	Tank disassembly	• Visual inspection • Foreign particle check	No abnormality No abnormality
		4-2	Transportation cover installation	• Fastening error check • Foreign particle check	No abnormality No abnormality
		4-3	Dry air substitution	• Dry air dew point • Internal pressure	-30°C or less Positive pressure
		4-4	Pre-shipment inspection	• Visual inspection • Internal pressure	No abnormality Positive pressure
5	Preparation of internal activity	5-1	Lifting	• Visual inspection	No abnormality
		5-2	Oil de-treatment	• Visual inspection	No abnormality
6	Internal lead disassembly	6-1	Disassembly	• Visual inspection • Foreign particle check	No abnormality No abnormality
		6-2	packing	• Packaging abnormality check (visual inspection) • Number of internal leads	No abnormality No missing
		6-3	Dry air substitution	• Dry air dew point • Internal pressure	- 30°C or less Positive pressure
		6-4	Pre-shipment inspection	• Visual inspection • Internal pressure	No abnormality Positive pressure

Major item			Work item	Management item	Example of criteria
7	Core Disassembly	7-1	Disassembly	- Visual inspection - Number of core and insulation parts - Foreign particle check	No abnormality No missing No abnormality
		7-2	Oil de-treatment	- Visual inspection - Number of iron core	No abnormality No missing
		7-3	Packing	- Visual inspection - Tightening check - Foreign particle check - Number of disassembly core	No abnormality No tightening abnormality No abnormality No missing
		7-4	Dry air filling of the transportation tank	- Dry air dew point - Internal pressure	- 30°C or less Positive pressure
		7-5	Inspection before shipment	- Visual inspection - Internal pressure	No abnormality Positive pressure
8	Winding disassembly	8-1	Lifting	Visual inspection	No abnormality
		8-2	Installation of monitoring insulation materials	Moisture content measuring	No abnormality
		8-3	Oil de-treatment	Visual inspection	No abnormality
		8-4	Film packing	Visual inspection	No abnormality
		8-5	Winding check	Insulation resistance	No abnormality
		8-6	Fixing	- Fastening check - Foreign particle check	No abnormality No abnormality
		8-7	Dry air filling	- Dry air dew point - Internal pressure	- 30°C or less Positive pressure
		8-8	Inspection before shipment	- Visual inspection - Internal pressure	No abnormality Positive pressure

Note: It is carried out when moisture absorbed by the dismantling work is removed. Depending on the manufacturer, it may be unnecessary to check the moisture content on the moisture absorption monitor material or to dry the coil before the factory test.

5.3 Transportation

Disassembled parts in the transportation unit are managed for impact during transport and the pressure sealed in the transport tank. Detailed management items are shown in Table 5.3.

Table 5.3 - Quality assurance details (Transportation)

Major item		Work item		Management item	Example of criteria
1	Transportation	1-1	Installation of impact recorder	• Visual inspection	No abnormality
		1-2	Pressure check in transportation tank	• Internal pressure	Positive pressure
		1-3	Loading	• Visual inspection	No abnormality
		1-4	Transportation	• Transportation speed: Normal Road Highway • Impact level	40 km/h or less 70 km/h or less 29.4 m/s ² or less
		1-5	Unloading	• Visual inspection	No abnormality

5.4 On-Site Works

The on-site assembly works of on-site assembly transformers is conducted by installing a clean house to ensure the same working environment as the factory. A dry air machine is installed to supply dry air to the house during assembly work to prevent moisture absorption of the insulation or rust of the iron core due to humidity rise. The clean house also manages dust and workers must wear clothing dedicated to internal work.

During core assembly, the core laminations are inspected visually for abnormalities in appearance such as dimensional measurement, position deviation, deformation, and damage. Furthermore, after the core assembly is completed, the core layer resistance and core insulation resistance is measured to confirm no abnormality.

When inserting the coil into the core, the horizontal dimension of the coil and the moisture of the test insulation block is checked.

Detailed management items are shown in Table 5.4.

Table 5.4 - Quality assurance details (On-site works)

Major item		Work item		Management item	Example of criteria
1	Clean house installation	1-1	Clean house installation	- Humidity - Floating dust amount	less than 50 % 80 % or less when the clean house ceiling is open 20 cpm or less
		1-2	Dry air generator installation	Dry air dew point	- 40°C or less
2	On base of main tank	2-1	Foundation Inspection	Flatness	Within manufacturer's criteria
		2-2	On base	Centering	Within manufacturer's criteria
3	Core assembly	3-1	Packing removal and Acceptance inspection	- Visual inspection - Impact level - Internal pressure	No abnormality 29.4 m/s ² or less Positive pressure (In case of using transportation tank)
		3-2	Winding dust-proof protective covering Prevention from moisture absorption	- Foreign particle check - Protective covering of windings - Humidity in Dust Proof Cover - Dry air dew point	No abnormality No abnormality 50 % or less - 40°C or less
		3-3	assembly	- Foreign particle check - Dimensions of stacking condition - Visual inspection	No abnormality equivalent condition with the factory No abnormality
		3-4	post assembly inspection	- Interlayer resistance - Insulation resistance	Within manufacturer's criteria
4	Winding assembly (Winding insertion)	4-1	Packing removal, acceptance inspection	- Internal pressure - Impact record - Visual inspection - Moisture content in insulation materials	Positive pressure 29.4 m/s ² or less No abnormality a) 0.5 % · wt. or less (500 kV class) b) 1.0 % · wt. or less (275 kV class) c) 2.0 % · wt. or less (154 kV class)

Major item			Work item	Management item	Example of criteria
				- Winding resistance - Insulation resistance	Factory test value: Within $\pm 5\%$ As per Figure 5.1 - Criteria of insulation resistance [6]
		4-2	Assembly (Coil insertion)	- Dimensions - Visual abnormality check - Dry air dew point - Foreign particle check	Horizontal (Within manufacturer's criteria) No abnormality - 40°C or less No abnormality
		4-3	Post-assembly inspection	—	— Note: not applying the inspection of winding itself
5	Internal lead assembly	5-1	Packing removal, Acceptance inspection	- Internal pressure - Impact record - Visual inspection	Positive pressure 29.4 m/s ² or less No abnormality
		5-2	Assembly	- Tightening torque - Abnormality check with drawings - Dimensions - Foreign particle check - Dry air dew point	Tightened within manufacturer's criteria No abnormality According to the drawing requirement No abnormality - 40°C or less
		5-3	post assembly inspection	Dimensions	No abnormality According to the drawing requirement
6	Tank assembly	6-1	Packing removal, Acceptance inspection	- Visual inspection - Internal pressure - Impact record	No abnormality Positive pressure (In case of insulation materials built-in) 29.4 m/s ² or less (In case of Coil, lead built-in)
		6-2	Assembly	- Foreign particle check - weather condition - Weld leg length - Degree of vacuum, N₂ concentration - Visual inspection	No foreign particle, workers' foreign particle, foreign particle generated during work Not rainy condition (In the case of work outside the clean house) Within manufacturer's criteria Within manufacturer's criteria No abnormality
		6-3	post assembly inspection	- Weld leg length - No Leakage check	Within the manufacturer specified value No leakage
7	Internal parts test	7-1	post assembly inspection	According to the field test item Table 5.5.1 On-site test items	Within manufacturer's criteria
8	Clean house disassembly	8-1	Clean house demolition	Visual inspection	No abnormality
9	Exterior parts assembly	9-1	Packing removal, Acceptance inspection	Visual inspection	No abnormality

Major item			Work item	Management item	Example of criteria
		9-2	Assembly	- Visual inspection check - Weather, Outside air humidity - Tightening torque	No abnormality such as deformation or damage on parts Not rainy condition, outside air humidity less than 80 % Tightened within manufacturer's criteria
		9-3	post assembly inspection	- Tightening abnormality check (visual inspection) - Insulation resistance	No tightening abnormality Within manufacturer's criteria
10	Bushing lead connection	10-1	Packing removal, Acceptance inspection	- Visual inspection check - Internal pressure - Impact record	No abnormality Positive pressure 29.4 m/s ² or less
		10-2	Assembly	- Protective covering abnormality (visual inspection) - Foreign particle check - Dry air dew point, Internal humidity - Weather, Outside air humidity - Worker clothes check (visual inspection) - Tightening torque - Dimensions - Number of in-tank carry-on parts and tools	No abnormality No abnormality - 40°C or less (Internal humidity 50 % or less) Not rainy condition, outside air humidity less than 80 % No abnormality with clothes Tightened The lead position is in accordance with the drawing dimensions No missing
		10-3	post assembly inspection	- Visual inspection - Dimensions	No abnormality According to the drawing requirement
11	Degassed lubrication	11-1	Acceptance inspection	- Insulation oil breakdown voltage - Moisture content in oil	Over 40 kV/2.5 mm Less than 30 ppm·wt. (500 kV Class)
		11-2	Oil vacuum pulling	- Moisture content in insulation materials (Before Vacuum drawing) - Degree of vacuum - Duration	a) Less than 0.5 %·wt. or less (500 kV class) b) Less than 1.0 %·wt. or less (275 kV class) c) Less than 2.0 %·wt. or less (154 kV class) a) Less than 67 Pa (500kV Class) b) Less than 133 Pa (275 kV Class) c) Less than 667 Pa (154 kV Class) Time depends on manufacturer

Major item			Work item	Management item	Example of criteria
				- Moisture content in insulation materials (Before oil impregnation) - Circulating oil amount - Settling time	a) 0.5 %·wt. or less (500 kV class) b) 1.0 %·wt. or less (275 kV class) c) 2.0 %·wt. or less (154 kV class) Oil Circulation x 2 times or more (500 kV Class) a) 72 hours or more (500 kV Class) b) 48 hours or more (275 kV Class) c) 36 hours or more (154 kV Class)
		11-3	Inspection after oil impregnation	- Insulation oil breakdown voltage - Moisture content in oil - Gas amount in oil - Oil-tightness pressure, Retention time - Oil leakage - Oil level - Moisture content in insulation materials	a) More than 60 kV/2.5 mm (500 kV Class) b) More than 50 kV/2.5 mm (275,154 kV Class) a) Less than 10 ppm·wt. (500 kV Class) b) Less than 15 ppm·wt. (275 kV Class) c) Less than 20 ppm·wt. (154 kV Class) a) Less than 0.5 %·vol (500 kV Class) b) Less than 1.0 %·vol (275 kV Class) c) Less than 2.0 %·vol (154 kV Class Below) More than 0.02 MpaG (more than 24 hours) No oil leakage All measurement should be Within manufacturer's criteria a) Less than 0.5 %·vol (500k V Class) b) Less than 1.0 %·vol (275 kV Class) c) Less than 2.0 %·vol (154 kV Class) (If it would be confirmed before vacuum drawing or before oil impregnation, cannot apply this item.)
12	Touch-up paint	12-1	Touch-up paint	Visual inspection	No abnormality
13	Final on-site test	13-1	Final on-site test	According to the on-site test items by Table 5.5 - On-site test items	Within manufacturer's criteria

" – " means those which do not define assurance standard values

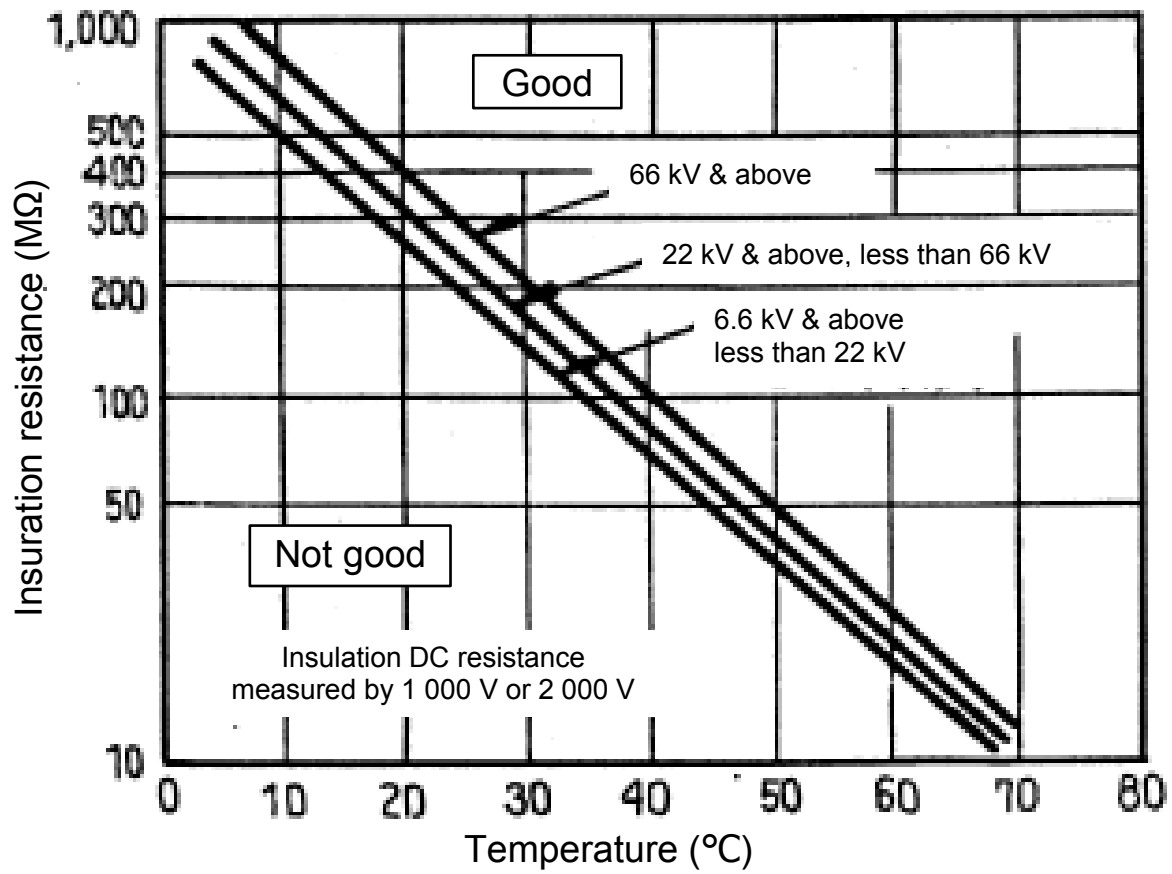


Figure 5.1 - Criteria of insulation resistance [6]

5.5 On-Site Tests

5.5.1 Introduction

Tests and inspections are performed at each stage. The tests performed are summarized the below table. The lead connections are confirmed by performing voltage ratio test and phase displacement test. The core and windings are confirmed by performing impedance, core visual check and core excitation test.

5.5.2 On-site test items

The on-site assembly transformer work should have the same quality control as in the factory. At each stage , a unique test shown in Table 5.5 is conducted. It is effective in ensuring quality and minimizing rework.

All the above-mentioned low voltage tests should be performed after the complete assembly.

Table 5.5 - On-site test items

Test item		Application		Remarks
		During on-site assembly	Finished assembly	
1	Core layer insulation, insulation resistance (between core layers and between blocks)	X	-	No abnormality check of core assembly condition
2	Short-circuit impedance with low voltage measurement	X	-	No abnormality check of core and coil assembly condition
3	No-load current with low voltage measurement	X	-	Core assembly condition check by low voltage excitation test (In order to avoid reworking, check core assembly condition) or measurement of excitation characteristics (AC·DC Superposition test)
4	Winding resistance measurement	X	X	a) During assembly No abnormality check during transportation, measure winding resistance as acceptance test of coil condition b) Finished assembly No abnormality check of coil assembly condition
5	Voltage ratio measurement	X	X	Lead connection check
6	D.C. insulation resistance	X	X	Insulation resistance check between windings and between winding and ground
7	Capacitance measurement	-	X	No abnormality check of core and coil assembly condition
8	Dissipation factor measurement (tan δ)	-	X	No abnormality check of core and coil assembly condition No abnormality check of moisture absorption surface of insulation materials
9	Polarity test	-	X	Lead connection check
10	Phase displacement check	X	X	Lead connection check

Test item		Application		Remarks
		During on-site assembly	Finished assembly	
11	On-load tap-changers - Operation test	-	X	
12	Insulation oil test (including DGA)	-	X	
13	Cooling equipment test (Including cooler control cubicle, oil pump, cooling fan, etc.)	-	X	
14	General structural check	-	X	
15	Oil tightness test	-	X	
16	Vacuum tightness test	-	X	
17	Auxiliary equipment test	-	X	

5.6 On-Site High Voltage Testing

Depending on the specification of the work, on-site high voltage tests can be carried.

5.6.1 Standards pertaining to on-site tests including on-site high voltage testing

The existing standards for on-site tests of power transformers are listed below:

- IEEE Std C57.93™-2019: IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers [19]
- IEEE Std 1861™-2014: IEEE Guide for On-Site Acceptance Tests of Electrical Equipment and System Commissioning of 1000 kV AC and Above [20]
- IEC TS 63042-301 Edition 1.0 2018-12 UHV AC transmission systems - Part 301: On-site acceptance tests [21]

All on-site test items are based on low voltage testing. Optionally, on-site high-voltage testing is described in the standards for UHV transformers.

Table 5.6 compares on-site test items for each standard. On-site high voltage testing is listed as an optional test by the existing standards on item 15.

Table 5.6 - Comparison of on-site test items on existing standards

Test item		IEEE C57.93-2019 [19]	IEEE Std 1861™-2014 [20]	IEC TS 63042-301 - 2018 [21]
1	Insulation resistance test	Insulation resistance test on each winding to ground and between windings.	Insulation resistance test on each winding to ground and between windings including bushings Core and frame insulation check	Insulation resistance test on each winding to earth and between windings including bushings Core and frame insulation check
2	Dissipation factor (tan δ) and capacitance measurement	Insulation power factor or dissipation factor test on each winding to ground and between windings. Capacitance should also be measured on each connection. In addition, core insulation should also be tested.	Dissipation factor (tan δ) and capacitance measurement on each winding to ground and between windings	Dissipation factor (tan δ) and capacitance measurement on each winding to earth and between windings including bushings
3	Tests on bushings	Power factor or dissipation factor test on all bushings equipped with a power factor tap or capacitance tap. Both C1 and C2 insulation should be measured.	Tests on bushings	Tests on bushings
4	Ratio tests	Winding ratio test on each tap. If LTC transformer, check winding ratio on all LTC positions.	Ratio tests	Ratio test
5	Winding resistance measurement	Check winding resistance of all windings with a Kelvin bridge or another suitable test device and compare with factory test results.	Winding resistance measurement	Winding resistance measurement
6	Liquid-level and hot-spot temperature	Check operation of liquid-level and hot-spot temperature indicating and control devices.	-	-

Test item		IEEE C57.93-2019 [19]	IEEE Std 1861™-2014 [20]	IEC TS 63042-301 - 2018 [21]
7	Insulating oil tests Dissolved gas analysis (DGA) test	Check dissolved gas, dielectric strength, power factor, interfacial tension, neutralization number, and water content of the dielectric liquid.	Insulating oil tests Dissolved gas analysis (DGA) test	Insulating oil test Dissolved gas analysis (DGA) test
8	Oxygen content and total combustible gas content	Check oxygen content and total combustible gas content of nitrogen gas cushion in sealed tank transformers. A total combustible gas test, where applicable, and a dissolved gas-in-oil test of the dielectric fluid should also be made soon after the transformer is in service at operating temperature to provide a suitable post-energization reference “bench mark.”	-	-
9	Auxiliary equipment	Check operation of auxiliary equipment, such as LTCs, liquid-circulating pumps, fans, or liquid or water flow meters in accordance with manufacturer's instructions.	-	-
10	Polarity check and excitation current measurements	Check polarity and excitation current at reduced test voltages.	Polarity check Excitation current measurements at reduced voltage	Polarity check Excitation current measurement at low voltage
11	Resistance, ratio, and polarity of instrument transformers	Check resistance, ratio, and polarity of instrument transformers when provided. These tests should be made at the terminal blocks in the control cabinet.	-	-
12	FRA	Frequency response measurement compared to factory results, if applicable. NOTE—If final bushings are not used in the factory, test results may differ.	Frequency response analysis (FRA)	Frequency-response analysis (FRA)
13	Leak testing	-	Leak testing with pressure (tightness test)	Leak testing with pressure (tightness test)
14	Short-circuit impedance measurement	-	Short-circuit impedance measurement at reduced current	Short-circuit impedance measurement

Test item		IEEE C57.93-2019 [19]	IEEE Std 1861™-2014 [20]	IEC TS 63042-301 - 2018 [21]
15	On-site high-voltage testing (as option item)	-	Optional tests based on the requirements of the user include the following: Applied voltage tests Induced voltage test with partial discharge measurement (IVPD)	Following items are optional: Induced voltage test with partial discharge measurement Applied voltage test NOTE Above optional test items are based on agreement between purchaser and supplier.

Note: “-“ means “no mentioned in the standards”.

5.6.2 Test items and its voltage levels

- (1) On-site high voltage tests and their corresponding test levels should be agreed upon between purchaser and supplier and documented.
- (2) The main test items should be induced voltage test including partial discharge measurement, applied voltage test, and in some cases impulse test.

5.6.3 Example of on-site high voltage testing reasons

Reasons for performing on-site high voltage testing are shown in Figure 5.2. One of the most important reasons is quality control after a repair or rebuild on-site.

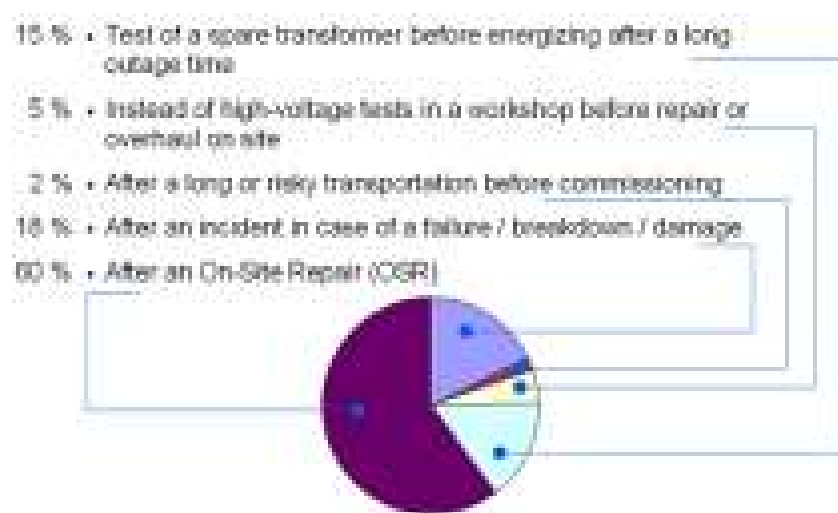


Figure 5.2 - Reasons for on-site high voltage testing on power transformers in Europe

5.6.4 Applying on-site high voltage testing

As seen in Figure 5.2, on-site high voltage testing can be done on new transformers and in service transformers. The main general reasons for doing the tests are:

- (1) Tests on new transformers (after a transportation event or after an assembly on-site)
- (2) Tests on transformers in service (after an event or failure)
- (3) Tests on a transformer on-site (before or after a repair on-site)

For all three categories, the scope of the tests as well as the test levels have to be agreed upon taking into consideration the space on site and test equipment capability.

For category (1), the on-site high voltage testing for the new transformer is an optional item in accordance with IEEE [20] and IEC [21] standards shown in Table 5.6. For new transformers that

have never been in service, it is recommended to perform at least the main HV tests at the full test levels according to the IEC-standard. The scope of tests for a new transformer after a transportation event can of course be reduced to induced and applied high voltage tests including PD measurements as well as a no-load test since the purpose is to check if the active part has suffered a fault during the transportation or not. The voltage levels applied in this case are usually below the FAT levels. This can also apply to transformers that have been repaired in a workshop with a transportation event.

If a new transformer is assembled on-site, the site tests might replace the FAT and thus all tests according to the standard should if possible be performed as final quality control. If the transformer was assembled before in the factory with an FAT before it was completely disassembled for transportation, the scope of the on-site tests might be reduced in consultation with the purchaser as shown Table 5.5. However, if technically possible, at least the induced voltage test with partial discharge measurement, applied test and no-load test is recommended

If on-site high voltage tests are not possible due to site limitations (not enough space, underground installation) then it should be noted that many successful projects of on-site assembly transformers with the quality assurance shown between clause 5.1 and 5.5 in this technical brochure were done without any on-site high voltage tests.

For category (2), the purpose of the test is a diagnostic procedure – e.g. to localize PD in case the DGA analysis indicates a failure. In these cases, high voltage tests are helpful to detect the failure and the test levels are usually below the allowed test levels in standards (or the original FAT). Very often the high voltage tests are performed in order to localize a PD defect, thus induced voltage tests with a level in a range of 120% of nominal voltage at increased frequency (e.g. 100Hz) are performed and additional equipment like acoustic or UHF PD sensors is used. Frequently single-phase induced tests on a three phase transformer and applied voltage tests are performed to localize the PD source as precise as possible.

Concerning category (3), different high voltage tests can be performed after a repair on-site, but the test levels are reduced compared to the original FAT test levels. In any case, induced voltage tests combined with PD measurements and applied voltage tests as well as a no load test is recommended. If the design of the transformer was changed during the repair, temperature rise test and lightning impulse test are recommended to verify the new design.

Sometimes a test before a repair is useful to get information on the condition of the core (no-load test) and whether the transformer has PD (induced voltage tests with PD measurement), but this is depending on the scope of the repair itself.

It can be concluded that today all high voltage tests on-site are possible, but the efforts increase with scope. Usually induced, applied and no-load tests can be performed using a main mobile testing facility (e.g. basic test container). More effort is necessary if temperature-rise tests are needed, because in these cases capacitive compensation is often needed, which requires a second device (container). The same applies to lightning or switching impulse tests, for which an additional device (container) is needed, with the restriction that chopped lightning impulses would again need an additional large device (container), thus these tests are not recommended, due to the large effort.

In cases with extremely large units in the range of 1000 MVA, it might be that basic tests can only be done.

6. Summary

Site Assembly of large transformers is shown to be a viable solution for severe transport limitations. Some countries (Japan in particular) have severe weight or size limitations for transport that make it near impossible to ship a transformer with a desired high MVA rating. Solutions have been developed that allow the transformer to be manufactured and then the windings and core dismantled to be shipped to site in several transportable segments for full assembly on site. A temporary building on site with a controlled environment is required for the assembly since windings and cellulose are exposed. Fixed cranes in site buildings or mobile cranes are used for the lifting. On site testing may be done after the site assembly.

A survey of site assemblies performed by several manufacturers in Japan, Europe and China showed the below solutions:

- A 3 phase 5 limb core design was shown to be typically utilized. The core is manufactured in 4 separate “U” cores that can be easily combined at site. The windings are nested together as a single phase for transport to site. At site the “U” cores are assembled on to a bell type tank base and the winding phases are landed onto the core main limbs. The transformer is fully assembled and tested in the factory before being dismantled and shipped to site.
- A 3 phase 5 limb core design was shown also where the core legs and yokes are shipped individually to site. A core stacking table is required at site where the bottom yokes are inserted. The core is up-righted and then the winding phases are installed. The top yokes are inserted, and the active part is installed.
- Solutions with shell form type transformers were shown
- A variant of the site assembly was shown to be the split tank type transformer. The transformer is divided into several tank components that are connected on site such that it will be an equivalent three phase or single phase required rating. For this type, the windings and cores are not assembled on site.
- These solutions have been done on hundreds of transformers globally and ratings above 1 500 MVA have been achieved. The field failure rate was shown to be very low.

A survey was similarly done for on-site assembly of existing transformers requiring new windings. In the event of failure, it may not be possible or practical to transport a transformer to a factory for repair. This may occur if rail lines or bridges have been decommissioned and the existing transformer can no longer be shipped out of the site in the same way it arrived. It is possible to disassemble the transformer and active part on site, and repair or replace damaged windings. This is termed “site repair” and involves many similar challenges and solutions as the above discussed on-site assembly. The survey included site repairs done in Canada, Europe, China and Japan.

The solutions for the site building / clean house were shown which are special purpose buildings that are reused and contain the necessary lifting systems or have removable roof panels for mobile cranes. It may be possible to use an existing building at site (i.e. generator hall with high bay ceiling and overhead crane) or a local company can prepare a tent type building on site. The site building must have a controlled atmosphere for low humidity and minimization of dust.

A survey was done for the dryout of the core & windings. The windings are manufactured in a transformer factory and dried out by vapor phase method prior to shipment. The various methods to limit moisture ingress during the site assembly process were shown. The final dryout was shown to be done by either hot oil / vacuum cycles, Low Frequency Heating (LFH) method or by site vapor phase.

The final testing of the assembled transformer at site varied in the survey. Some manufacturers test the assembled transformer in the factory (and some only as design tests on the first transformer) and then only perform low voltage tests at site. Other manufacturers do full testing at site on the assembled transformer but with no factory testing. All situations were proven to be successful with low field failure rates.

Technology was shown to have been developed for mobile test equipment to allow all parameter and dielectric verification tests to be performed at site. Loss measurement, impedance measurement, temperature-rise test, applied voltage and induced voltage are performed using AC HV test equipment. Lightning impulse voltage and switching surge voltage tests are performed with a mobile HV impulse test set. DC tests such as DC applied or DC induced voltage tests are performed with mobile DC test equipment.

Modern mobile AC HV test systems utilize an Electronic Power System (EPS) which can vary the output

voltage and output frequency across a wide range during operation. The system includes an inductive and capacitive compensation and a step-up-transformer that can be switched manually into many different configurations. By using external capacitor banks, a temperature-rise test can be also performed at site with this system. Transformers up to 800 kV have been tested with this type of mobile AC HV test system for induced, applied and loss measurement. Temperature-rise testing is limited by available capacitors and the power supply (i.e. typically a very large 2 MW diesel generator).

The HV mobile impulse test set is a modified version of a factory impulse test set where the test circuit lays down flat into a 40 ft. ISO container or road trailer for shipment. Mobile impulse sets that can perform testing up to 1 800 kV BIL are in use and higher voltages are technically possible.

The methods and quality controls were surveyed by several manufacturers. Detailed quality checks, testing, clean house requirements, processing / dryout and inspections are shown.

It was overall demonstrated that varying solutions have been developed and successfully executed for site assembly and site repair for more than 20 years. The increased risks of performing tasks at site such as installing windings, core assembly, active part dryout and dielectric testing have all been managed. The site assembly and site repair are shown to be a viable and a fully possible solution when required in accordance with local regulations, practices, and its specifications.

These on-site assembly and on-site rebuild are a new technical survey for the power transformer. This technical brochure shows different procedures with many experiences of the on-site assembly and the on-site rebuild. They show good reliability with FAT and on-site acceptance tests without on-site high voltage testing (Japan in particular). This technical brochure summarizes the sequences of quality assurance for the on-site work.

APPENDIX A.

Detail of the factory and on-site tests methods for the on-site assembly transformers in Japan

Disassembly and transportation of power transformers: On-site work quality management standards

No.	Factory Test						On-site Test			
	Test Items	Test Type				Contents of the test Test Contents	Test Items	When to Test Timing	Contents of the test Test Contents	
		JEC-2200 ^[22]			Original			During Assembly		Finished Product
		Acceptance	Type	Special						
1	Winding resistance measurement	○	—	—	—	Measure winding resistance between each winding, each phase, and each tap by Kelvin double bridge or voltage drop method	Winding resistance measurement	▲	▲	Measured between each winding, each phase, each and tap by a low resistance meter or voltage drop method
2	Transformer ratio measurement	○	—	—	—	Measure transformer ratio between each phase and each tap of each winding question by transformer winding ratio tester or voltmeter method	Transformer ratio measurement	●	△	Same as factory test contents
3	Polarity test or phase displacement test	○	—	—	—	Measured by vector method or kick method	Polarity test or phase displacement test	▲	△	Same as factory test contents
4	Low voltage short circuit impedance measurement	—	—	—	○	Apply low voltage and low current at rated frequency and to measure short circuit impedance	Low voltage short circuit impedance measurement	●	▲	Measured by low voltage and low current of rated frequency
5	Short circuit impedance and load loss measurement	○	—	—	—	Apply a current of 50% or more of the rated current at the rated frequency and measure	Short circuit impedance measurement	—	—	—
6	No-load loss and no-load current measurement	○	—	—	—	Excitation measurement with rated frequency and rated voltage	Low voltage excitation current measurement	—	△	Measure no load current with a low voltage of about 200 V (do not measure no load loss)
7	Short-term alternating current withstand voltage test	Induced Test	○	—	—	Apply AC voltage using generator etc. (Verify the insulation strength between winding and ground, between each winding, between turns, and between taps)	AC withstand voltage test (Equivalent to a on-site withstand voltage test)	—	▲	Conducted with alternating voltage using pressure resistance test equipment or generator Test voltage, test duration, etc. are in accordance with the provisions of the electrical equipment technical standards
		Apply Test	—	—	—	Same as above (Verification of insulation strength between winding and ground and, between windings)				
8	Long-term alternating current withstand voltage test (Including partial discharge measurement)	○	—	—	—	Measure a partial discharge amount by applying a relatively low voltage for over a long time to a transformer exceeding 187 kV	Long time excitation test	—	▲	Excitation for 4 hours with three-phase 100% voltage at the rated tap, and to performing various measurements
9	On-load tap changer test	○	—	—	—	After installing the transformer, perform the specified tap switching and to confirm that it works properly function	On-load tap changer test	—	○	Perform tap switching and check that it works properly to confirm proper function
10	Temperature rise test	—	○	—	—	Supply the total loss to the transformer mainly by the short circuit method, and to measure the oil and winding temperature rise values	Load test (Corresponds to the on-site temperature rise test)	—	△	Conducted by the actual load method and measure the oil temperature rise value measurement (Wound temperature rise measurement is not performed)
11	Lightning impulse withstand voltage test	—	○	—	—	Apply specified test voltage To (Verify the insulation strength of each winding against the lightning impulse)	—	—	—	—

No.	Factory Test					On-site Test			
	Test Items	Test Type			Original	Test Items	When to Test Timing		Contents of the test Test Contents
		JEC-2200 ^[22]					During Assembly	Finished Product	
		Acceptance	Type	Special					
12	Capacitance measurement	—	—	○	—	Capacitance measurement	—	●	Same as factory test contents (It may become impossible to measurement by induction may not be possible due to an from the adjacent existing transformer)
13	dissipation factor measurement (tan δ)	—	—	○	—	Dissipation factor Dielectric loss angle measurement	—	●	Same as factory test contents (It may become impossible to measurement by induction may not be possible due to an from the adjacent existing transformer)
14	Insulation resistance measurement	—	—	○	—	Insulation resistance measurement	○	○	Same as factory test contents (It may become impossible to measurement by induction may not be possible due to an from the adjacent existing transformer)
15	Noise level test	—	—	○	—	Noise level test	—	▲	Perform noise level measurement in accordance with the long-time excitation test
16	Zero phase impedance measurement	—	—	△	—	—	—	—	—
17	Overload resistance test	—	—	△	—	—	—	—	—
18	Short circuit strength test	—	—	△	—	—	—	—	—
19	Transition voltage measurement	—	—	△	—	—	—	—	—
20	Natural frequency measurement	—	—	△	—	—	—	—	—
21	Harmonic component measurement of no-load current	—	—	○	—	—	—	—	—
22	Insulation oil test (Including gas-in-oil analysis)	—	—	○	—	Insulation oil test (Including gas-in-oil analysis)	—	○	Same as factory test contents
23	Cooling equipment test (Includes cooler control panel, oil feed pump, and cooling fan)	—	—	○	—	Cooling equipment test (Includes cooler control panel, oil feed pump, and cooling fan)	—	○	Same as factory test contents

No.	Factory Test						On-site Test			
	Test Items		Test Type			Contents of the test Test Contents	Test Items	When to Test Timing		Contents of the test Test Contents
			JEC-2200 ^[22]		Original			During Assembly	Finished Product	
			Acceptance	Type						
						current and input loss				
24	General structure inspection		—	—	—	○ Check whether each part is assembled according to the drawing, dimensions of each part, attachment condition, painting condition, etc.	General structure inspection	—	○	Same as factory test contents
25	Iron core interlayer resistance/ insulation resistance measurement		—	—	—	○ Measure the insulation resistance of core block between layer, between core and earth, between core and clamp, between each block of core, etc.	Iron core interlayer resistance/ insulation resistance measurement	●	—	Same as factory test contents
26	Excitation Characteristics	Low voltage excitation characteristic test	—	—	—	○ Apply a low voltage at the rated frequency and to measure the excitation current of each phase	Excitation Characteristics	●	—	Same as factory test contents
		Core excitation characteristic measurement (AC · DC superposition test)				○ Apply low voltage of AC and DC, and to measure admittance with magnetic flux equivalent to rated voltage				Core excitation characteristic measurement (AC · DC superposition test)
27	Calculation of voltage regulation and efficiency		—	—	—	○ Calculated based on the standard from the results of no load test and short circuit impedance test	—	—	—	—
28	Control circuit withstand voltage test		—	—	—	○ Apply test voltage between control circuit and ground	—	—	—	—
29	Surge impedance measurement		—	—	—	△ Apply a rectangular wave pulse with a low voltage impulse voltage generator and measure it with the second Kyoto University method	—	—	—	—
30	Oil-tightness, airtightness test		—	—	—	○ Pressurize the inside of the transformer outer box, to check it can withstand pressure, and confirm that there is no oil leakage	Oil-tightness, airtightness test	—	○	Same as factory test contents
31	Vacuum test		—	—	—	○ Check the vacuum resistance of the transformer outer box	Vacuum test	—	○	Same as factory test contents
32	Vibration measurement/ acceleration measurement		—	—	—	○ Apply rated voltage at rated frequency, and to confirm that there are no absence of abnormal vibration or noise on the tank surface and accessories.	Vibration measurement	—	▲	Conduct vibration measurement in line with long-term excitation test
33	Potential distribution measurement		—	—	—	△ Check the potential oscillation in the coil Generally implemented at the content stage during production	—	—	—	—
34	Winding leakage current measurement		—	—	—	○ Operate the pump at rated speed and to check the winding leakage current value flowing to the neutral point	Winding leakage current measurement	—	○	Same as factory test contents
35	On-site high voltage test capacity measurement		—	—	—	△ Confirm the power supply capacity of the local withstand voltage test	—	—	—	—
36	Long-term charge test (Normal ground voltage)		—	—	—	△ Excitation for a long time over a long period at rated voltage and to check for abnormal gas generation	Long-term charge test	—	▲	Conducted according to the long-time excitation test
37	Auxiliary equipment test		—	—	—	○ Confirmed that the accessories itself has themselves the performance according to the specifications The Bushing type current transformer performs polarity test and insulation resistance	Auxiliary equipment test	—	○	Conducted operation check, insulation resistance measurement, polarity test, operation test of alarm circuit, etc. for each part

No.	Factory Test					On-site Test			
	Test Items	Test Type			Contents of the test Test Contents	Test Items	When to Test Timing		Contents of the test Test Contents
		JEC-2200 ^[22]					During Assembly	Finished Product	
		Acceptance	Type	Special					
				Original					
					measurement after installation				
38	Seismic test	—	—	—	△ Check the mechanical strength of the bushing and body anti-seismic hardware etc. in the earthquake proofing statement	—	—	—	
39	Pipe flow rate measurement	—	—	—	△ Measured by ultrasonic flowmeter	—	—	—	
40	Frequency response analysis	—	—	—	△ Variable frequency oscillator measures frequency response characteristics of coil	Frequency response analysis	—	△ Same as factory test contents	
41	Tap winding Frequency response measurement	—	—	—	△ Apply a variable frequency and low voltage and to measure the frequency-response magnification characteristics of the tap winding	Tap winding Frequency response measurement	△	— Same as factory test contents	
42	—	—	—	—	—	AC excitation current measurement	—	△ Apply single-phase low voltage and measure each phase current value	

○, ●: Standard implementation (●: Disassembly transport transformer specific test)

△, ▲: Conducted by some manufacturers or in consultation (▲ ; Disassembly transport transformer specific test)

—: Not performed

Note: Fluid charge maintenance may be conducted with dielectric loss tangent and insulation oil electrification measurement in consultation with the user

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