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Spare transformers – A new approach for managing risk

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ABSTRACT

The Norwegian TSO has developed a new policy for spare transformers as a mean to optimize transformer fleet operation and risk management. After this policy was approved in 2012, we procured four new spare transformers especially designed as spares. The TSO has rented a warehouse to keep these transformers indoor with their accessories partly in special storage containers procured with the transformers, but two permanent spare transformer warehouses are in the planning phase. Further spare transformers as an autotransformer 420/300 kV, 1000 MVA, and spares for the TSO's 132 kV and 66 kV transformers are envisaged.

This paper discusses the background for the procurement of new spare transformers, the risk evaluation and the special design requirements for the transformers. These may be transport limitations, overload capabilities, installation with up to three different conservator location and five different rail gauges, description of the four procured special spare transformers, and the thermally isolated, heated and ventilated storage containers for the accessories.

Main message is the risk of an N-2 failure involving transformers may be underrated due to very low probability, but extremely high consequence of Energy Not Delivered as substations normally are planned for an N-1 failure only. This contingency was covered in a technical-economical viable way by procuring specially designed spare transformers.

KEYWORDS

Risk management, risk vs. consequence, spare transformer, spare design, preparedness considerations

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1. Risk vs reliability, underrating of N-2 failures

The basis for all design of High Voltage (HV) transformers is the need to safeguard sufficient margins against the occurring overvoltages in operation, and this is done by verifying design, and especially quality of manufacturing, by performing the specified tests during FAT. However, the basic studies deciding each manufacturer's insulation design, based on the (1 min) Design Insulation Levels used for the different test voltage, has for each design inherently a certain statistical failure rate. This is based on the fact the insulation margins must be based on a technical-economical optimization founded on the chosen insulation design for toughest of the specified test voltage levels. Each manufacturers insulation design is based on the wanted/chosen parameters in the Weibull distribution found from the results during the testing of the different designs.

This fact is rather basic for dealing with HV insulations system, but is often overlooked when evaluating the risk for an N-2 situation in a substation. There is no such thing as a "Zero-failure" design for HV insulation!

An electrical insulation system, i.e. here the power transformer in the grid, normally has a life development as in Figure 1 from [1]. After the initiating period in Phase 1, a hopefully long period in Phase II resumes with mainly stochastic failures with a constant failure rate, before the period with increased ageing in Phase II will weaken the component towards end-of-life considerations or failures.

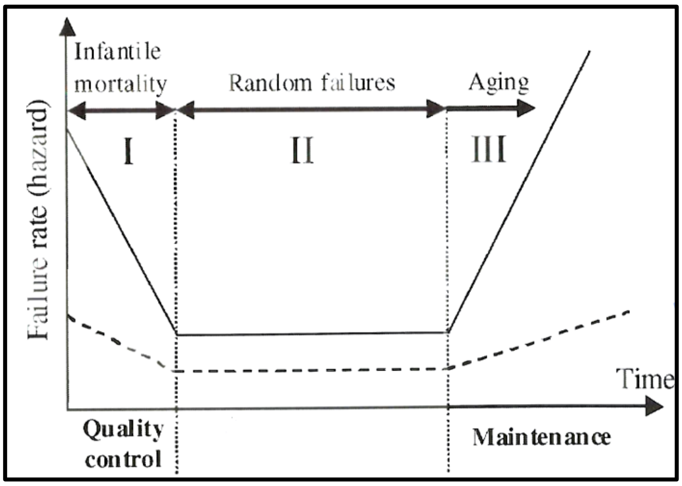

Figure 1 The "Bathtub" curve.

An important distinction in Phase II is the insulation system may weaken from "external" causes, which may be detected by diagnostic means. Hence, it is normal to divide the rather constant failure rate in Phase II in two parts:

1. A stochastic part for failure (non-ageing induced and normally which cannot be easily detected), and
2. a part for failures that may be detected.

Failure rated reported in national and international failure statistics surveys are mostly the constant failure rate in Phase II. The dotted curve is the failure rate experienced when diagnostic methods are used, especially regular or continuous analysis of failure gases (to find e.g thermal faults, which is a typical non-ageing induced fault mode).

The main point here: The Asset Manager may easily underrate the consequences of failures in Phase II, especially N-2 failures, where two (or more!) transformers fail at or about the same time. This may be due to the two transformers having the same design, or specification, weaknesses. The Assett Manager then may have some very bad nights wondering about the identical sister standing in the next pit to the failed transformer.

Planning for only N-1 situations you will inherently underrate the possibility for an N-2 failure in the repair or substitution time for the failed transformer. It is here the use of prepared and special spare transformers will reduce your risk of N-2 failures by swiftly replacing the failed transformer and keeping the risk acceptable, even with a dubious twin unit.

It is important also to stress when the normal risk evaluation of probability times consequence seems to be acceptably low, and the probability is very low, *it is necessary to evaluate the consequence alone* and skip the risk figure as the controlling parameter. Neither the population (our customers), the Regulator nor the owners accepts high consequences of a substation failure whatever the low probability is.

2. Evaluation of acceptable risk, number of spare transformers

The need for a new policy on spare transformers emerged when the TSO in 2011 commenced a huge investment and reinvestment program caused by two events. Firstly, new renewables emerged in a high degree (some wind, but a high number of small-scale hydro power plants) where most of the energy is fed into grid areas already with surplus power/energy. Hence, the energy has to be fed into the transmission system and moved to areas in Norway with an energy deficit or exported to other countries (Denmark, Sweden, the Netherlands and soon to Germany and UK).

The transmission system in Norway is mainly on 300 kV level, but also with some 420 kV lines. During the last 15-20 years many projects increased capacity, but without making new OH lines, mainly new or bettered system protection schemes and thermal upgrading of OH-lines. However, around the year 2000 this source of postponing new investments were exhausted. Due to this and the experience from some major black-outs (examples): Denmark and Sweden in 2003-5 million people affected, Moscow 2005-2 million people, collapse started by a transformer failure, Chile 2010- 15 million people affected, transformer failed, Chile 2011 with 9 million people, Brazil 2011-53 million people.

Not all these grid collapses were caused by transformer failures, but it increased the Board of Director's awareness of good contingency planning and the need for spare parts, including transformers. No dedicated spare transformer designed as such existed in 2011, but almost all substations fulfilled the N-1 criteria in operation. However, the risk of another failure of the neighbouring transformer (or other equipment in the transformer circuit), possibly caused by the same failure mode due to the higher loading and the same design, was clearly underrated.

The risk involved investigated in 2011-2012 with this basis for the probability analysis performed:

1. Operational policy limits a maximum power outage to 200 MW and a restoration time of maximum one hour. This is also valid for a transformer failure.

2. If a new transformer failure causes Energy Not Delivered for more than two hours, a spare is needed. Other criteria exists for loss of water (hydropower generators), capacity in "spot corridors" or main grid cuts, or maximum operational voltages.

3. Maximum installation time for a spare transformer is four weeks.

4. Estimated maximum repair time for a transformer is one year, but average repair time is six months.

5. Minimum one spare transformer for a certain ratio must exist if a long time outage occurs.

6. The TSO's transformer failure rate for serious failure (10 year average in 2011) is 0.4 %, CIGRÉ reports 0.32 % in [2].

7. Due to a considerable uncertainty margin in the failure statistics, the analysis was performed for both 0.3 % and 1 % failure probability.

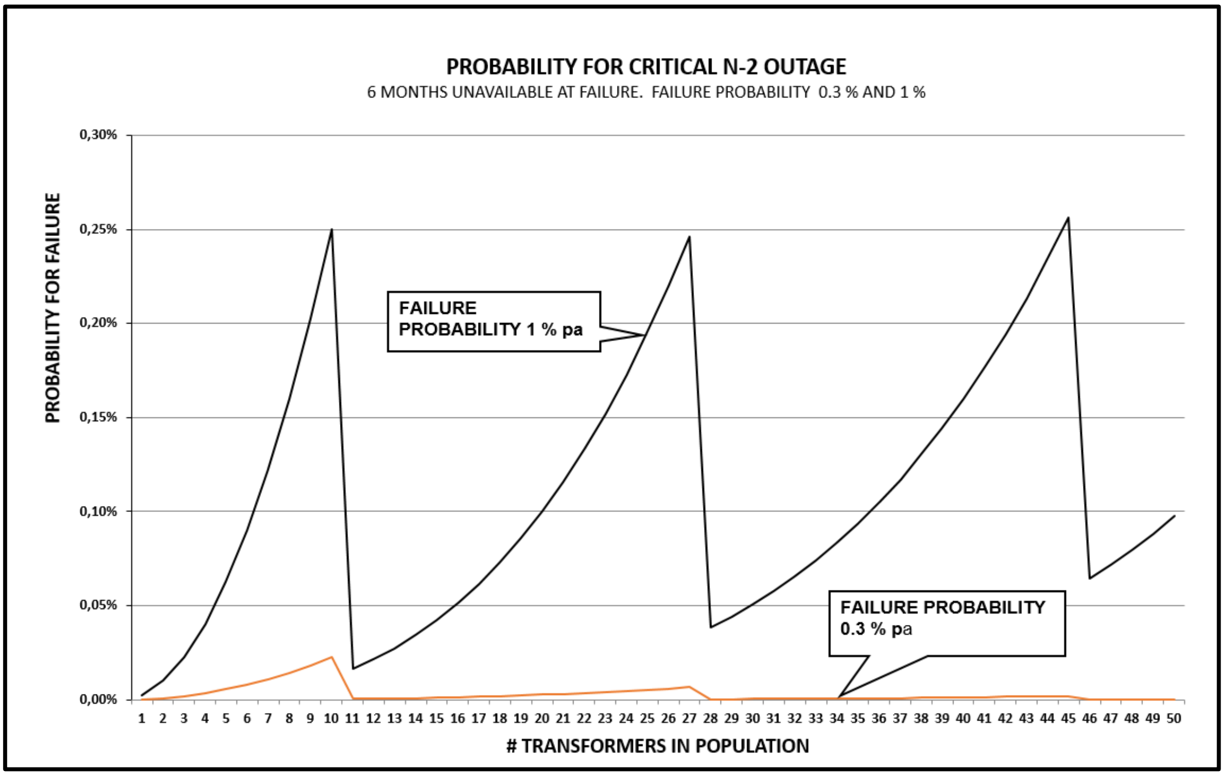

Figure 2 Probability for N-2 outage.

When the single spare transformer is used, no spare exists for this ratio/power until the failed transformer is repaired/replaced (average time 6 months), and the analysis illustrated the risk involved by having different number of spare transformers given a probability for failure and a number of transformers in the ratio/power group (population). Hence, the analysis addressed the risk involved by having a specific number of spares. This analysis gave the picture in Figure 2:

With a population of 10 transformers and one spare, and a failure rate of 1 %, and 6 months to re-establish a normal operating situation with a repaired transformer, the probability is 0,25 % for a failure without an available spare unit (N-2). Hence the "average return time" for such an event is 400 years.

If we consider this risk to be an upper limit for the acceptable risk, the number of spare units must increase with one to two units when transformer number 11 arrives in the population. Further, given the same argument, the number of spare units must be increased to three when the population exceeds 27 transformers, and to four spare units when the population exceeds 45 transformers. These results are calculated as independent failures. This is not always true if the grid has several transformers of the same design/age/manufacturer.

It is useful to remind the reader the average failure probability, average time to re-establish wanted capacity after a failure, and the variation of these parameters, highly influences the results. Experience also shows that the top management risk aversion is highly dependent on when the last outage giving Energy Not Delivered occurred. It seems to be a global rule top management risk aversion (willingness to take a risk) declines dramatically after a severe outage with Energy Not Delivered. The media race for scapegoats and the eventual negative influence on other business sectors as energy or service sales in the concern may also influence the level of acceptable risk involved in the grid operation.

3. Design of a spare transformer.

The TSO's main rules for a dedicated spare transformer (outside of N-1 in each substation) are:

1. A spare transformer shall be stored cold, filled with oil, and accessories assembled on the transformer, or in dedicated storage containers (see below). This avoids costly transformer bays, switchgear and protection equipment.

2. All stored transformers must be registered in the Enterprise Resource Planning System as individuals with its technical, contingency and environmental parameters stored.

3. Where several spare transformers are stored at the same geographical location, a Risk and Security analysis will evaluate the risk for unwanted events that may involve several of the stores units and its accessories.

4. Actions must be taken to avoid damaging oil spill during storage.

5. A spare 300 kV transformer is normally designed also for connection to the 420 kV transmission system (reconnection through access openings under the cover by changing position of links).

6. For transformer LV level of 69 kV, the reconnection to 138 kV is always required to cover a future voltage upgrade of the customers grid. It is anticipated the long-term solution for all 33 kV, 50 kV and 66 kV grids is they will be upgraded/changed to 132 kV.

7. Both 300 kV and 420 kV grids are solidly grounded. (Almost) all 33 kV, 66 kV and 132 kV grids in Norway are grounded by high impedance earth fault reactors ("Petersen-coils"). Exceptions are the 132 kV grids in and around the cities of Oslo and Bergen, which both are (partly) low impedance grounded grids with some neutrals solidly grounded and others grounded through a 60 or 45 Ohm current limiting air reactor.

The Norwegian TSO does normally require overload capability according to IEC 60076-7 Power transformers - Part 7: Loading guide for oil-immersed power transformers. When a higher loading is necessary than stipulated in Table 4, a higher hot-spot or oil temperatures are allowed, see below for Spare 3.

The following spare units procured after 2012:

1. Spare 1, 420-300± 16x1,4 % / 138-69 kV, 250 MVA, rail transport profile 1, transport weight 185 metric tons. (Taps referred to 300 kV)

2. Spare 2, 420-300 ± 16x1,4 % / 138-69 kV, 160 MVA, rail transport profile 2, transport weight 150 metric tons.

3. Spare 3, 420-300 ± 12x1,4 % / 50 kV, 160 MVA, *installed* weight 225 metric tons.

4. Spare 4, 420-300 ± 12x1,4 % /138/47 kV, 300 MVA, transport weight 250 metric tons. This unit is a spare for five units in four bulk substations where the capacity in the customers 132 kV cable grid is limited so that neighbouring substations cannot take over the full load.

The Spare 1 and Spare 2 transformers are spares for a combined population of 76 transformers and further spares are envisaged. These two transformers have each two sets of HV bushings, one set for 420 kV and another for 300 kV bushings, each set with one spare bushing. This is due to the small size of some of the transformer bays in the 300 kV substations. The 300 kV bushings are special design with increased length on the oil part.

Transformer bushings are normally of RIP design with outer polymer, and all new transformers are "porcelain free" to reduce collateral damage at a bushing failure (not on HVDC transformers).

Spare 1 has a detachable OLTC to make this rather big 250 MVA transformer tank fit within the rail profile, see Figure 4.

Figure 3 Spare 2 during FAT with 420 kV bushings.

Spare 3 had to be specified with maximum *installed* weight. The transport plans did not limit the transport weight, but to avoid recalculating the civil design for 16 transformer pits to check them for an eventual new maximum installed weight, the minimum installed weight of all 16 transformers (240 metric tons) was specified as the maximum installed weight of the new spare unit. The factual weight of 225 metric tons installed gave a nice margin for potential old flaky concrete and rusted reinforcement bars under some transformer jacking pads.

Spare 3 inquiry specified minimum long-time overload capability of 1,5 per unit (p.u.) at 0 °C ambient air temperature. Hence, a higher hot-spot winding temperature was allowed with a rise of +90 K (i.e. a hot spot reference temperature of 110 °C) and not the hot-spot winding temperature rise of +78 K (i.e. a hot spot reference temperature of 98 °C) as for a "standard transformer". The Design Review showed the increased hot-spot temperature was not needed and a long-term overload at 1,65 per unit is possible at 0 °C ambient air temperature. This makes this spare unit rather useful in an emergency.

The increased overload current has to be checked for bus-bars and switchgear in each substation when needed. The protection relay plan has to be changed too, as the TSO regularly trip transformers at 1,4 p.u. current and at low temperatures, with top-oil temperature trip at 95 °C and winding temperature trip at 115 °C. These settings are easy to change on the transformer WTI and OTI when needed in an emergency.

Figure 4 Spare 1 with detachable OLTC and conservator on tank in warehouse.

For all new transformers a heat run test is specified which shall be sped up by introducing 130% overload during the first 6 to 8 hours prior dropping to the total losses. Due to the installed fibre-optical sensors the real hot-spot and oil temperatures are checked and the margins to specifications are of course of interest to Operations when operating a spare in an emergency situation, where the fibre optics may be used during an emergency loading situation.

To facilitate a SFRA measurement during the FAT also when the bushings shall not be installed because the transformer is a cold spare, a set of 1 kV test bushing are located on all bushing transport covers on the tank, and the winding leads are connected to the test bushing and grounded there. Two full sets of SFRA measurements are performed during FAT, with the bushings installed and with the test bushings installed, but the latter without oil. Hence, a set SFRA measurement will be taken in the transformer warehouse in Norway before the tank is filled with oil. These measurements will be the template for future measurements when the spare transformer is moved to a substation to be put in service.

4. Transport and transformer pits.

The Spare 3 transformer is designed for all the TSO's rail gauges: 2x1500 mm, 2x1800 mm, 2x2400 mm (all with mid-rail) and 3000 mm without mid-rail, together with the standard 1435 mm for longitudinal movements.

Spare 4 is designed for 2x1500 mm, 2x1800 and 2x2400 mm (all with mid-rail). However, the Spare 3 and the Spare 4 had to be designed for two types of wheels:

First set of outer wheels are the "standard wheel" with a 20 mm flange where the wheels passes the rail crossings with the loading on the wheel flange with a steel "bit" located in the rail crossing.

The second set of outer wheels are the "Oslo-wheels" for the four bulk substations the TSO recently bought from the utility in Oslo. Here it is necessary with a 50 mm flange on the outer wheels because the loading is on the flange during passing of the rail crossing, due to the welded crossings (as in the "frog" of a tramway point). The result was the bottom plate of this Spare 3 unit has 118 (!) threaded holes all plugged to avoid corrosion and paint in the bolt holes.

Spare 3 is also prepared for three different location of the oil conservator: On the transformer (standard solution), on the wall with piping to the tank, on separate support consoles to the floor. All these solutions are in use for the 16 units where the Spare 3 may be needed.

We prefer to move the spare transmission transformers on one of two vessels designed for transport of one of the three girder hangers with the transformer on the deck between the girders. All vessels and girder hangers with tow trucks are owned by the TSO through our transport subsidiary. However, to some substations, the railways are used and with different transport profile depending on the branch line, Spare 1 and Spare 2 have different rail loading profile. This restricts the size and power of these two spares. We have our own rail girder waggon for some of these rail transports (weight limitation).

5. Storage and accessories.

As laid down by the Energy Regulators preparedness regulations, the spare transformers are stored so that the transport and installation may commence rapidly without major dismantling.

The four spare transformers are stored in a cold warehouse without the accessories installed, and with oil. All the accessories except bushings and radiators are stored in thermally insulated storage containers with heating, ventilation and humidity controlled fans to avoid condensation.

Figure 5 Storage containers for accessories.

These containers are procured with the spare transformers. The roof is detachable to enable lifting out the crates and the galvanized containers are equipped with sockets for external cable to supply electricity to heating and ventilation. All containers have double external earthing lugs.

The containers are painted and marked with text labels according to the approved Design Handbook for all equipment.

The conservator is located on the tank and is only filled with some oil as the temperature is quite stable in the warehouse. Oil-spill detection equipment will be installed by sending the Oil-low signal from the Buchholz (no oil/high gas) to a Security monitoring centre. An oil resistant mat is located under the transformer and over a rim to contain any oil spill.

The spare transformers are stored on each side of the warehouse to allow the girder hanger to move in between the transformers.

Al-alloy Duplex line clamps for the bushings and arrestors, together with double tier clamps and wires to connect to existing drops to the failed transformer will be prepared. The bulk substations have three types of wire in us: Pheasant, Solros and Narcissus and it is not practical to procure three different sets of clamps to all spare transformer.

Conclusion

Following approval in 2012, the Norwegian TSO procured four new spare EHV transformers especially designed as spares. The TSO has rented a warehouse to keep these transformers indoors with their accessories partly in storage containers procured with the transformers. The TSO is currently considering establishing a permanent spare transformer warehouse. The spares have significantly improved the contingency preparedness situation for the TSO.

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Short Bio of Main Author

Kjetil Ryen is a senior adviser on transformers in the Norwegian TSO Statnett. He was born in Oslo in Norway in 1953 and has B.Sc. in electronics from Oslo Technical College in 1974 and a Siviling degree (M.Techn.) in Power Engineering from the Norwegian University of Science and Technology in 1986. He has worked as a tramway and metro engineer in Oslo until he changed to the "AC world" of HV substations in 1987 working in engineering and management positions in several Norwegian utilities. He is in Statnett since 2008. Ryen is a member of IEEE PES, IAS and DEIS since 1996 and was elected Senior Member of IEEE in 2004. Ryen is a member of the Norwegian IEC TC 14 group (NEK NK 14) for 15 years, member of CIGRÉ where he has participated in some WGs as A2.20 *Economics of Transformer Management* and A2.36 *Transformer Procurement Process*, where he directed the revision of the TB on Design Review, and he now participates in A2.42 *Guide for Transformer Transport*.