Dryformer™

a new type of oil-free power transformer with low environmental impact

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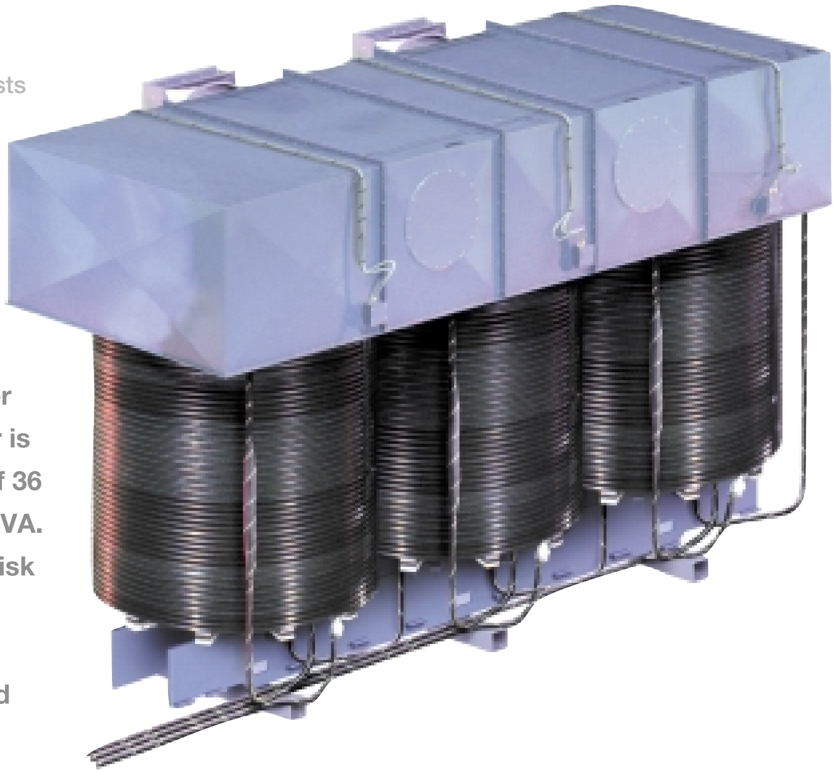


Dryformer™ is a new oil-free high-voltage transformer based on cable technology first used in ABB's revolutionary new generator, Powerformer™. Forced-air cooled, it has innovative windings made from dry polymer cables with circular conductors. Dryformer is designed at present for primary voltages of 36 to 145 kV and power ratings of up to 150 MVA. The absence of oil means that there is no risk of ground or water pollution in the event of damage and a much smaller risk of fire or explosion. Dryformer can therefore be sited closer to the consumer, for example below ground and in urban or ecologically sensitive locations. Because the electric field is fully contained within the XLPE cable and the cable surface is at ground potential, Dryformer offers unique opportunities for optimizing power transformer design.

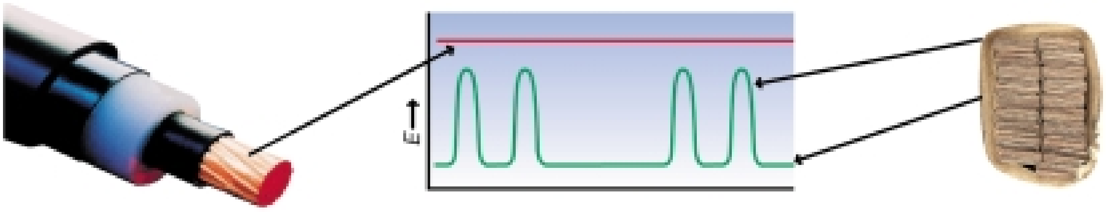
Dryformer™ is a new type of dry power transformer that breaks entirely with tradition. Based on the same high-voltage power cable technology that is used in Powerformer™ [1], ABB's revolutionary new generator, it is constructed with cylindrical windings that overcome the field distribution limitations existing with conventional power transformer design.

Innovations

Rectangular conductors are used for windings in conventional power transformers in order to maximize the current rating. This shape results in an uneven field distribution with high field strength at the corners. To keep the eddy current losses in the windings to a minimum, the conductors have to be transposed along the winding in an elaborate configuration. In the winding-end region, intricate measures also have to be taken to control the

1 Circular versus rectangular conductors: in accordance with Maxwell's equations, the electric field distribution is even with round, XLPE cable and there are no partial discharges (paper-insulated conductors shown on the right).

E Electric field



electric field and prevent partial discharges.

In accordance with Maxwell's equations, the cylindrical conductors used in Dryformer's windings distribute the electric field evenly 1. Another advantage of round conductors is that there are no small corner radiuses, as in the case of rectangular conductors, to limit the maximum permissible field stress.

With modern insulation materials and production techniques, 500-kV cables accommodating field stresses up to 15 kV/mm can be manufactured today. Conventional rectangular oil/cellulose coil insulation does not allow such fields.

The cable has an outer semiconducting layer which remains at ground potential. The electric field is thus completely confined within the cable, providing transformer manufacturers with a whole new range of possibilities for the electrical and mechanical design.

Cable

As already mentioned, the windings used in Dryformer consist of insulated cable similar to conventional solid high-voltage dielectric cable. Around the conductor is an inner semiconducting layer, followed by a solid dielectric and the outer semiconducting layer. The solid dielectric is cross-linked polyethylene (XLPE).

The conductor is normally of the 'concentric lay' type, having a center wire surrounded by concentric layers of nominally 6, 12, 18, 24, 30, 36 and 42 wires. Each layer is applied with an alternate direction of lay.

The outer semiconducting layer of the cable remains at ground potential. This has a number of advantages. First, there is no risk of partial discharge or corona occurring anywhere in the winding. Second, personnel safety is substantially improved, since all exposed surfaces of the transformer are at ground potential.

Rethinking the design parameters for transformers

The electrical and mechanical design of conventional power transformers is complex, partly because account has to be taken of electric and magnetic fields, temperature and mechanical forces which have a mutual effect on each other.

Since the electric field is confined entirely within the cable, design parameters such as the distance from winding to

Historical background

Today's transformer technology has its roots in experiments carried out with single-phase distribution transformers in Hungary in the early 1880s. By the end of the same decade they were being sold in various parts of the world, mainly to supply electricity to local lighting schemes in major cities. The first three-phase system with a three-phase transformer was the Hellsjön 9.6-kV transmission system, set up in Sweden in 1893. All of these early transformers were dry types.

Mineral oil was used for the first time around 1906, when it became necessary to build transformers for voltages above 20 kV. It is still used in power transformers today, nearly a century later. Technological advances have meanwhile pushed the voltage as high as 800 kV and the power above 1000 MVA.

Traditional dry-type transformer designs have precluded output voltages exceeding 36 kV.

winding and from windings to grounded parts can be dealt with separately. With the distances minimized, all the design engineer has to consider is the space needed to ensure sufficient cooling.

Dryformer further eliminates one of the most critical aspects of conventional transformer design - the need for measures to limit the influence of the electric field on grounded parts. Because it is completely contained within the cable there is no need to control the electric field in the winding-end region, as is the case for conventional dry-type distribution and oil-immersed transformers.

The induced voltage in a power transformer increases gradually along the HV winding from the neutral end to the line end when the transformer is connected to a directly grounded system. Thus, the cable used for the HV winding is subjected to different electrical stresses over the length of the winding. A feasible solution is therefore to use thinner insulation for the first winding turns and subsequently increase the insulation thickness. One way of doing this, and which allows the volume of the transformer core to be utilized better, is to use different cable dimensions along the winding.

The temperatures in the core and windings can easily be monitored by direct measurement on the actual material. Continuous forced-air cooling is used to cool the core and windings 2. Dryformer can be temporarily overloaded until the temperature of the hottest winding reaches a level of 80°C. The cooling philosophy adopted for Dryformer is based on 100% redundancy. For example, if one fan is required to keep the temperature below 70°C at full load, the transformer will be delivered with two identical fan systems. If the temperature rises above 70°C, two things happen: an alarm signal is sent to the control room and the back-up fan switches on automatically to cool the transformer to below the design temperature. Having two fans makes it possible to temporarily overload the transformer for several hours.

Each fan can be equipped with an optional frequency-controlled fan speed regulator to reduce fan power consumption at low load and low ambient temperature.

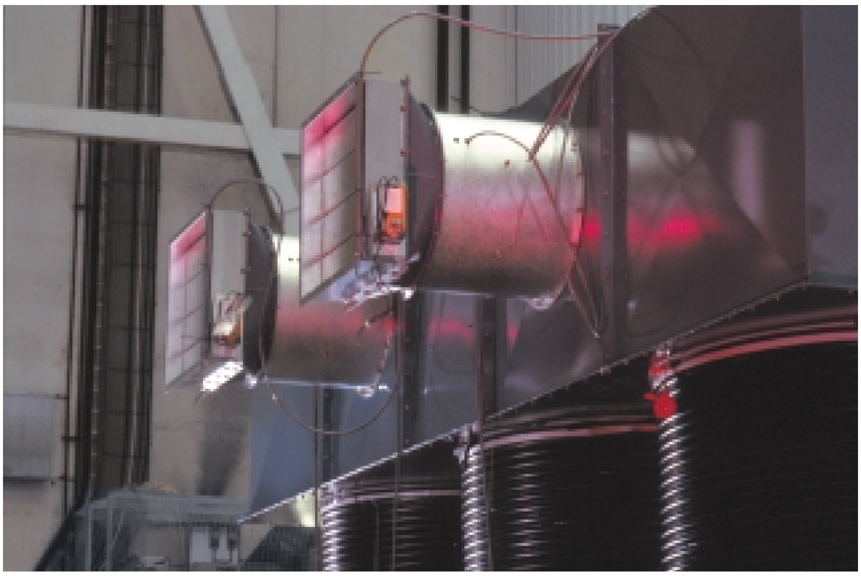
New manufacturing techniques

The core of Dryformer is manufactured in a very similar way to that of conventional transformers and uses the same type of core lamination. The only difference is that corrosion-inhibiting paint is applied to the complete assembled core to make up for the absence of oil.

Dryformer and conventional oil / cellulose transformers differ mainly with regard to their windings. In the case of conventional transformers, the winding work is the most sensitive part of the production process. Experienced personnel are needed to insulate (mainly by hand) the bare conductor with cellulose strips and carry out the often complicated winding. It is easy to see how fabricating and handling the insulated cable used in Dryformer simplifies the design and production processes.

The insulated cable for Dryformer is produced and tested in the cable factory,

2 Forced-air cooling system. One fan is for the continuous load, the other is redundant. An optional speed regulator reduces fan power consumption at low load and low ambient temperature.



3 Dryformer gives electric utilities and local authorities more flexibility when siting substations and makes it easier to comply with environmental legislation.

leaving the transformer manufacturer with just the less complicated winding work. Eliminating the sensitive cellulose handling and all oil handling processes greatly reduces the risks involved in winding production.

Simpler production processes and pretesting in the cable factory also help to keep cable delivery times short.

The fact that Dryformer contains no oil makes it especially well suited for use in densely populated urban areas. Dryformer gives electric utilities and local authorities more flexibility when siting substations 3 and makes it easier to comply with local environmental laws and regulations. Substations can be designed independently of the power transformer. Also, cost-savings are likely to arise from an optimized substation layout, reductions in the required fire-fighting equipment, and the elimination of the oil pit.

Since Dryformer can be connected direct to insulated high-voltage cables, it is possible to place it closer to the final distribution system. Generally speaking, the transformer can be located wherever the power is consumed, inside or outside buildings, above or below ground, even outside of the substation. By bringing the high voltage closer to the power consumer, Dryformer reduces the losses in the supply cables, thereby having a major impact on the cost of the power lines and cables.

The advantage of being able to site the transformer in urban areas is illustrated in 4, which shows the effect of installing Dryformer 5 km closer to the load. By moving the transformer, 69-kV cable (instead of 24-kV cable) can be run right up to the load center, resulting in lower losses. 4b quantifies this saving over a period of 30 years (total 8.5 GWh, or 280 MWh per year - transformer losses not included). The saved losses can also be expressed in terms of reduced emissions (see *Table*).

None of the risks associated with oil – pollution of the environment, fire and explosion – apply. The absence of oil also means that high-voltage power

Table: Saving in losses gained by installing Dryformer™ 5 km closer to the load center (see 4), expressed in terms of reduced emissions (kg/30 years) for different countries

	CO_2	SO_2	NO_x
Sweden	345,400	2,200	900
Canada	1,870,000	8,400	4,700
Denmark	8,180,000	34,700	21,000
USA	5,601,000	21,500	14,000

transformers can be located close to waterways. Hydro-electric power stations and water treatment plants are other sensitive locations where water has to be kept free from pollution.

Another advantage of having no oil and the electric field being contained within the cable is that the usual risks involved in installing HV power transformers in high-rise buildings are eliminated.

The use of HV cables and cable joints instead of overhead lines in urban areas may also eliminate possible risks associated with open electric fields, as high-voltage parts are not left exposed.

Maintenance

With fewer components, Dryformer requires less maintenance and offers higher reliability and availability than conventional transformers. The absence of oil, besides simplifying and speeding up installation work, also eliminates the risk of consequential damage resulting from explosion and fire.

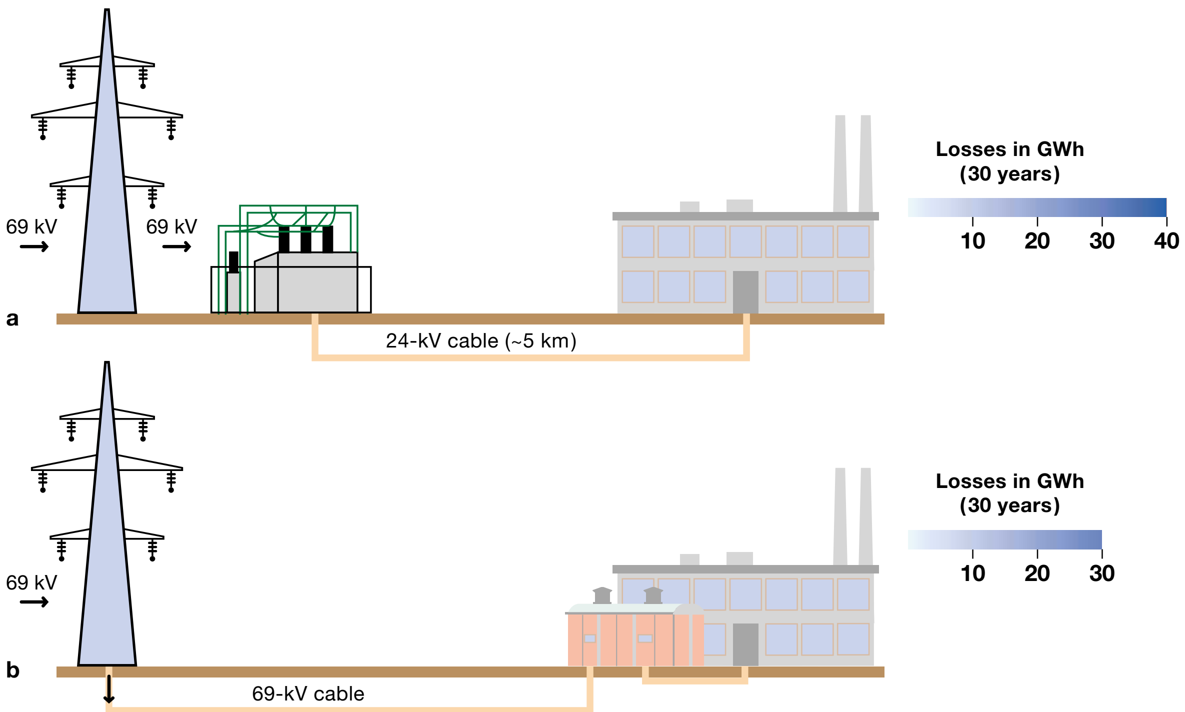
Environmental impact

Environmental protection has been a primary concern throughout the history of dry-type transformers. To study the overall environmental impact of a product or system, from raw material extraction to final disposal, including production and use, a life-cycle assessment (LCA) has to be performed. The results show that Dryformer is more environmentally friendly than equivalent conventional transformers.

Economic impact

It is standard practice to analyze the overall substation economics before investing in power equipment. Such an analysis has to look at the capital investment, revenues, the cost of operating the plant, and interest rates, etc. Typical examples are Life Cycle Cost (LCC) and Life Cycle Profit (LCP) analyses.

4 Saving in losses achieved with Dryformer. Siting the power transformer 5 kilometers closer to the load enables 69-kV cable to be used (instead of 24-kV cable) for the extra distance. Quantified over a 30-year period, the total saving is 8.5 GWh, or 280 MWh per year (b).



Due to the nature of present-day transformer technology, vendors tend to offer similar performance and operating characteristics. The performance of Dryformer affords advantages beyond those of a conventional transformer which make it crucially important for the evaluation to look beyond the first-time cost.

The following cost factors have to be considered on a case-to-case basis:

- Costs relating to the substation, for example geographical location, layout and elimination of the oil-pit, etc.
- Protection and supervision
- Installation
- Fire and explosion protection
- Losses
- Reliability (MTBF[1] and MTTR[2])
- Environmental impact

Alternative solutions apply in each case. A cost evaluation model has been developed for Dryformer which makes it possible to calculate the total savings for each individual tender.

Optimization packages

Transformer enquiries are very often based on old specifications, which themselves can be based on how the system looked 10 to 20 years ago. The Dryformer concept creates unique possibilities for optimizing both the transformer and the network.

1 *MTBF = Mean Time Between Failures*
2 *MTTR = Mean Time To Repair*

Electrical design

As an option, ABB can optimize Dryformer for existing systems. This includes an evaluation of the actual system requirements, covering:

- Rated power
- Rated voltage
- Voltage regulation (number of steps, step voltage)
- Insulation levels (coordination with other components)
- Short-circuit impedance
- Loss evaluation
- Noise level

Mechanical design

Optimization of the mechanical design is another option available with Dryformer. This may be necessary, for example, when older transformer specifications do not meet the requirements of a new substation concept or when a specially designed solution is needed for a special location. Possibilities include:

- A dedicated design for indoor or outdoor installation of the enclosure
- Special location of the cooling equipment
- Special location of the tap-changer, terminations, etc

New dry tap-changer and cable terminations on the way

While the first Dryformer units have been supplied for applications not needing on-load tap changers, a new type of dry tap changer is currently under development. This and a new type of dry cable termination that is also being developed will be presented at a later date.

Outlook

The first Dryformer to enter commercial operation was installed in December 1999 at a hydropower station owned by Swedish utility Birka Energi on Sweden's east coast. This unit, which is rated at 20 MVA and 140/6.6 kV, is located in a small URBAN substation. The URBAN concept was developed as an indoor solution for substations rated up to 170 kV. The incoming connections are made via cables instead of overhead lines.

The second Dryformer unit (25 MVA 78/11 kV) was installed in one of Stora Energy's hydropower stations, located on the Ljusnan river in central Sweden, in May 2000.

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Reference

[1] M. Leijon: Powerformer™ – a radically new rotating machine. ABB Review 2/98, 21–26.