e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

Contract number	308908	**Instrument**	Collaborative Project
Start date	1st of September 2012	**Duration**	40 months
WP 3	**Technology portfolio to meet the 2050 scenarios**		
D3.1	**Technology assessment from 2030 to 2050**		

Annex to D3.1 - Technology Assessment Report

Transmission technologies: Transformers, Phase shifting transformers, transformers with tap changers and AC breakers

Revision	Organisation	Date
Written by	J. Roos and P. Lundberg (T&D Europe)	09.07.2014
Checked by	E. Peirano (Technofi)	09.07.2014
Validated by	G. Sanchis, B. Betraoui (RTE)	

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

Document information

General purpose

This document is an annex of deliverable D3.1 focusing on the technology assessment (technical and economic performances) of generation, storage, transmission and demand-side technologies. This report focuses on the key components of the transformers (phase shifting and tap changers) and AC breaker technology. It provides an explanation of the key variables selected, the methodology for the data construction as well as a technical outlook as of today and 2050.

The present document is complemented by an attached Excel file providing the data compiled according to the methodology described in the in the next sections.

Change log

Revision	Date	Changes description	Authors
V1.1	3rd June 2014	Comments by Technofi on draft proposed by T&D Europe	Technofi
V1.2	9th July 2014	Final version	T&D Europe

Table of content

Transformers and AC breaker technology

This report focuses on the key components of the transformers (phase shifting and tap changers) and AC breaker technology. It provides an explanation of the key variables selected, the methodology for the data construction as well as a technical outlook as of today and 2050.

1 Introduction

Transformers and AC breakers are key components in the transmission network.

The technology components are divided in the following sub-categories:

- Phase shifting transformers
- Transformers with tap changers
- AC breakers

Phase shifting transformers (PST) are crucial components in the ongoing strive for improved AC network efficiency. Increasing amounts of transmitted energy push the networks to the limit, increasing the risk of network instability. PSTs are a cost-effective means to ensure reliable and efficient power flow control in overloaded transmission lines.

Key functions of PSTs are:

- Load sharing of parallel lines
- Boost transmission capacity without violating the N-1 criterion
- Boost system reliability
    - mitigation of post-contingency overloads
    - mitigation of unwanted power transfer
- Allow access of new generation to the grid, for example wind turbine parks
- Remove bottle necks in the grid caused by bulk power injection

Power transformers with tap changers (TAP) Power transformers are key components in connecting AC networks of different voltage to each other. These power transformers must be built to withstand severe electrical stress from fault currents and transients. Their availability and longevity have a major impact on grid reliability and profitability.

Key functions of TAPs are:

- Voltage step-up and –down
- Slow dynamic regulation to adjust to changing network conditions supporting voltage stability of the ac-grid

AC breakers or circuit breakers are critical components in the electrical systems that has the capability to, in the shortest possible time, switch from being an ideal conductor to an ideal insulator and vice versa. Furthermore, the circuit breaker should be able to fulfill the following requirements:

1. In the stationary closed position, conduct its rated current without producing impermissible heat rise in any of its components.
2. In its stationary positions, open as well as closed, the circuit breaker must be able to withstand any type of overvoltages within its rating.
3. The circuit breaker shall, at its rated voltage, be able to make and break any possible current within its rating, without becoming unsuitable for further operation.

Key functions of AC breakers are:

- Coupling of busbars, transformers, transmission lines, etc.
- Interrupt fault currents

- Protect electric and electronic equipment.
- Intentional switching such as energizing and de-energizing of shunt reactors and capacitor banks.

2 Technology performance characteristics

2.1 Variables selected for phase shifting transformers

Four technical characteristics have been selected, the final one (security of supply) being itself measured by four specific technical variables.

2.1.1 <u>Transmission losses – index of losses per transformer unit in percentage of rated power [%].</u>

Computation: losses are measured in percent of the nominal rating of the transformer unit during load and no-load.

2.1.2 <u>Transmission capacity – maximum power at which each transformer unit can be operated (MVA)</u>

Computation: measuring voltage units X current capacity

2.1.3 <u>Phase angle – maximum operational phase angle</u>

Computation: measured in degrees

2.1.4 <u>Security of supply – overall variable</u>

Computation: result from four specific technical variables listed below. It is assumed that it is also impacted by the commercial availability and the integration in operation of other critical equipment and systems.

2.1.4.1 <u>Reliability – index of the likelihood of a contingency event</u>

Computation: number of trips per unit and per year [Nb/y].
A contingency event is defined by either loosing part of the power of the totality of it[1].

2.1.4.2 <u>Availability – Probability of finding the component/device/system in the operating state at some time in the future.</u>

Computation: scheduled energy availability as a percentage of the total number of hours per year [%].

2.1.4.3 <u>Maintenance (frequency) – interval at which scheduled outages are planned. This variable impacts the Availability variable as well as the cost of maintenance.</u>

Computation: interval of maintenance [scheduled outages frequency].

2.1.4.4 <u>Maintenance (outage time) – amount of time required to perform maintenance</u>

Computation: applies either to the whole equipment or to part of it [number of weeks or days per maintenance outage].

2.2 Variables selected for transformers with tap changers

The variables selected are the same as the ones identified above for phase shifting transformers.

[1] Traditionally the specifications of the network design might allow for some trips per year of part of the power; but losing all the power is allowed only in extreme cases.

2.3 Variables selected for AC breakers

The variables selected are the same as the ones identified above for phase shifting transformers (except for rated power, which is not included for AC breakers).

2.4 Assumptions for the expected evolutions of technical data from 2013 to 2050 for transformers and AC breakers technology

This section is organized in two subsections:

- The first one presents some technological insights for each of the above selected variables of the transformers and AC breakers as seen by manufacturers at the current stage of development (2013).
- The second one is focused on the technical outlook at 2050 and the underlying assumptions to project trajectory of technical performances.

2.4.1 Technical outlook today (2013)

The technical outlook for transformers and AC breakers technology at the current stage is carried-out for the two selected technologies of transformers (PST and with tap changers) as well as for AC breakers.

In the following sections a technical outlook for the selected technologies are presented per selected variable.

2.4.1.1 Transmission losses in transformers

The technology of both selected technologies is mature, which indicates a lower likelihood of larger developments in the future. The state of art is mainly limited by the complexity of transportation, project adaptation of the product for each project and the limited number of suppliers that master this technology that is rather challenging for a transformer manufacturer. Each sub technology is well-known but the combination that occurs in this project is challenging since we need to respect the transport profiles and other physical limits to make the product realizable.

PSTs allow you to control the power flow in the transmission grid independently of the generation. Total power flow is influenced by modifying the load share of parallel lines. System reliability is improved by mitigation of post-contingency overloads and of unwanted power transfer. By balancing the power flow in the network and optimizing the electrical power flow, grid owners can minimize the electrical losses in their system.

TAP

The transformer equipped with tap-changer are the commonly used transformer technology and is in practice the dominated transformer technology. The development is mostly on material and loss optimization, thus getting more efficient use of existing technology due to the presence of better simulation tools that can predict the behavior of the design. For both transformer technologies, losses around 0,3% per transformer unit today is normal and no significant improvements is foreseen.

2.4.1.2 Transmission losses in AC breakers

The technology of AC breakers is mature and further based on mechanical design resulting in close to zero losses in the equipment. No significant improvement in the loss figures is foreseen.

2.4.1.3 Transmission capacity

PSTs are often the most economic and reliable approach to power flow management and system design, enabling you to get more out of their existing assets. Existing transmission lines can be loaded up to the thermal limit without being overloaded. The investment in new lines can be postponed or even avoided. The key challenge is to do a grid planning so that the PST will have sufficient operating range for the future expansions.

Both transformer technologies and AC breakers can be designed to handle the commercially highest available voltage levels. Further increase in voltage levels can be limited by other implications such as transportation feasibility.

2.4.1.4 Security of supply for transformers

Four variables have been chosen to measure Security of supply as detailed in the table below. It should be mentioned that reliability, availability and maintenance variables are at about the same level in 2013 for both transformer technologies.

Variables for Security of supply	Today (2013)
Reliability	1 trips per 10 year
Availability	99,9% per unit
Maintenance (frequency)	every 5th year per unit
Maintenance (outage time)	8 hours / year per unit

A modern core and coil arrangement and an optimized tank design support low electrical losses, enabling efficiency levels of up to 99.9 percent. Operating and maintenance costs are comparable to the costs of a net coupling transformer and therefore much lower than most power electronic devices.

The maintenance requirements are indicative since they are highly dependent on number of operations over the life-time of the equipment.

Further, it is assumed that in order to secure a given level of supply, different measures could include strategies based on redundancy of system components, technology development of key equipment, processes and methodologies, etc.

2.4.1.5 Security of supply for AC breakers

Four variables have been chosen to measure Security of supply as detailed in the table below.

Variables for Security of supply	Today (2013)
Reliability	1 trips per 10 year
Availability	99,9% per unit
Maintenance (frequency)	every 15th year per unit
Maintenance (outage time)	8 hours / year per unit

The maintenance requirements are indicative since they are highly dependent on number of operations over the life-time of the equipment.

Further, it is assumed that in order to secure a given level of supply, different measures could include strategies based on redundancy of system components, technology development of key equipment, processes and methodologies, etc.

2.4.2 Technical outlook at 2050 for transformers and AC breakers

The coming generations of transformers, AC or DC applications, will be characterized by a shift on environmental focus. The responsibility of reaching a lower impact on the environment will be shared between producers and users. It includes all steps from production to operation over the life-time of the equipment and decommissioning/recycling. This shift will impact the following areas:

- Design and manufacturing: design is key to optimize the use of materials. A combination of efficient use of steel, cupper, oil, transport weights and losses is the result of a closer co-operation between manufacturers and users to focus more on functional requirements rather than detailed specification. Further, manufacturers will be required to produce equipment with a minimum impact on the environment in the production process.
- Operation: Life-time assessment will become more important.
  - One of the most important variables to consider is the losses. Manufacturers will be required to optimize losses for the operation and to enable a high quality system to verify the actual losses during operation.
  - An increased utilization is another critical variable to consider, which leads to increase of speed on return on investment for the users. This will put a higher focus on design of the actual hot spot. Incorrect design or non-optimized can lead to temperature rise by 6-8 degrees on the actual hot spot, which decreases the life-time significantly.

Phase shifting transformers protect transmission lines and HV equipment from thermal overload, improve transmission system stability and control the power flow between different networks, for parallel long distance overhead lines or for parallel cables. PSTs are highly complex power transformers, with more windings and tap changers than traditional power transformers and a large number of connections between the three phases. Since every unit is unique, a detailed insight into the transformer's design and the system environment in which it operates is essential.
The phase shifting transformers have been available for a number of years and from a technical point the technology is mature. The coordination is relying on the work from the transmission system operators by using coordinated control. This is today more a legal and economical challenge then a technical challenge. Since PSTs are used to limit power flow to re direct one can see them as 'road-blocks' and the increased use of FACTS and HVDCs will limit the growth of this market. That is the reason why we expect a flat performance curve over the years.

AC breakers
The requirements on live tank circuit breakers may be as high as 80 kA current interrupting capability and 800 kV rated voltage. In addition to live tank circuit breakers, there are also other constructions of the circuit breaker poles (dead tank, GIS). In earlier times, oil and compressed air were typical insulating and extinguishing medium. Nowadays they are almost entirely replaced by SF6 gas for economical and practical reasons, and also due to increased demands for higher ratings. The environmental concerns of SF& is handled through a strict handling of this medium during the lifetime. Alternative medium do exist but this is an economical/environmental optimization that can change over the years but will not pose any technical challenge.
There are different types of operating mechanisms, e.g. spring-, hydraulic- and pneumatic-operated mechanisms, and recently digitally-controlled motors have come into use.

2.4.2.1 Transmission losses in transformers

The technology of both selected technologies is mature and indicates a lower likelihood of larger developments in the future.

Fort both transformer technologies the reduction of losses will be a continuous focus area, although the advancements expected are smaller than for other active technologies.

For PST, losses around 0,3% per transformer unit today is normal and no significant improvements is foreseen.

For TAP, losses around 0,3% per transformer unit today is normal and is forecasted to stay on this level for the coming decades. However, with the advancement of superconductivity materials the losses can be further improved on a long-term basis.

2.4.2.2 Transmission losses in AC breakers

The technology of AC breaker technology is mature and indicates a lower likelihood of larger developments in the future especially on losses since they are already today close to zero.

2.4.2.3 Transmission capacity

Both transformer technologies and AC breakers can be designed to handle the commercially highest available voltage levels. Further increase in voltage levels can be limited by other implications such as transportation feasibility.

2.4.2.4 Security of supply

All variables of security of supply are foreseen to have limited, if any, further development in order to reach higher system performance. Reliability, availability and maintenance variables are expected to stay on the same levels in 2050 for all technologies.

One of the main driving forces of many transmission networks is the need to improve the security of supply. This will impose more stringent requirements also on future transformers and AC breakers. However, due to the relatively high availability figures today little advancement on this are anticipated.

2.5 Methodology for data gathering

The methodology for data gathering has been consistent for all active technologies.

- For each technology a first set of data parameters were identified by a group of key experts within T&D Europe. These data parameters or variables were selected based on their economic and technical importance for the active technologies when it comes to choosing the future grid technologies from a planning perspective. The parameters reflect the key technical parameters that have and will be the base for specifying the transmission schemes during planning, construction and evaluation phases of each future project.
- This set of parameters were verified and approved in T&D Europe. The assumptions were verified by a larger group of experts inside T&D Europe that agreed on the link between the selected data set and the relevant parameters.
- An appointed expert group collected the data and prepared a first draft during several workshops with 5-10 experts from organizations in T&D Europe
- The data gathering sources are reference projects, published articles and R&D plans that give the robustness needed to the figures. One element of concern in this approach can be the transparency for some partners and stakeholders outside of T&D Europe; however, T&D Europe believes that a combination of hard facts from relevant reference projects, including the history and some quantitative and qualitative assumptions, are a sound base for the dataset. Although such an approach will always lead to interpretation, T&D Europe believes that this is a fair and appropriate way of collecting data.
- The data gathering of VSC technology was presented in WP 3 group meeting as test of this approach to gathering the relevant data for the datasheets. The method was judged valuable since this prediction are for a long time and must be judged on a combination of hard and soft facts and be evaluated. You have to mix todays, product, academic results

and visions. It was agreed to use this approach to be used for the remaining active transmission technologies.

- After compilation of data parameters for all active transmission technologies, a second round of validation, with all the relevant stakeholders, is performed before submission of the present report to the e-Highway 2050 coordinator. The robustness will be further explained in the next section.

Mode	Type of data gathering	Nature of data processing	Comment
Own expertise	informal knowledge captured by interviews with internal experts	Modelling	Yes
		Data gathering	Yes
	knowledge formalized in published articles	Modelling	Yes
		Data collection	Yes
Other experts of the field	informal knowledge captured by interviews with external experts or workshops	Modelling	N/A
		Data gathering	N/A
	knowledge formalized in published articles	Modelling	N/A
		Data gathering	Yes
	knowledge structured in State of the Art studies	Modelling	N/A
		Data gathering	N/A
Other mode (please describe)		Modelling	N/A
		Data gathering	N/A

Figure 1 : Modes for data gathering.

2.6 Conclusions on robustness of the produced data

The methodology for verification of data robustness has been consistent for all active technologies. All data have been verified in several steps including workshops with experts from the T&D Europe organization to increase the confidence in the results.

All data corresponding to technical variables of the active technologies have been evaluated during the data gathering process based on their probable market readiness over the time horizon for the project.

As a consequence, the data has the best possible confidence for each time horizon: today, 2020, 2030, 2040 and 2050.

For some of the key parameters in the data sheets uncertainty levels have been approached by including value ranges. The uncertainty is handled by providing min and max values, which shall contribute to increase the robustness of the data.

3 Technology readiness and maturity

3.1 Variables selected

The selected technologies' readiness and maturity have been measured according to the TRL scale.

3.1.1 PST – Phase shifting transformer

Computation: TRL index

3.1.2 TAP – Transformers with tap changers

Computation: TRL index

3.1.3 AC breakers

Computation: TRL index

3.2 Assumptions for the expected evolutions of technical data from 2013 to 2050 for HVDC technology

Technology readiness level is a quantitative index reflecting the degree of maturity of a given technology (and each of its components). The mark (from 1 to 9) synthesizes the expected evolutions described in the technical outlook as of today and in 2050.

Technology readiness and maturity		**Time horizon**				
		2013	**2020**	**2030**	**2040**	**2050**
Phase shifting transformers		9	9	9	9	9
Transformers with tap changers		9	9	9	9	9
AC breakers		9	9	9	9	9

From this table the following conclusions can be drawn:

All technologies are already mature technologies.

For the Transformers with tap changers and the AC breakers there are some component development which could lead to a change in the TRL once these components are ready to be introduced.

3.3 Methodology for data gathering

Data gathering on maturity of technologies relies on expertise of T&D Europe members.

3.4 Conclusions on robustness of the produced data

See 2.4.2 and 2.5

4 Possible implementation constraints

4.1 Variable selected

The physical sizing (surface occupation) is a constraint that is included in the “environmental impact and public acceptance” data type (see chapter 6).

Although other variables influencing implementation constraints could be evaluated, they are more related to the owner’s perspective rather than to the manufacturer’s side.

4.2 Context of implementation constraints for transformers and AC breakers

The transformer and AC-breakers are already today a very integrated cornerstones in our power systems. The acceptance of these devices from a public acceptance and environmental impact will be judged by the audible footprint, the loss levels mainly. The actual physical footprint will also be essential since the discussion of ‘not in my backyard’ discussion are judged to become more and more common in the years to come.

5 Costs

5.1 Variables selected

5.1.1 CAPEX – Capital investment in Euros per kW installed [€ /kW]

Data to be provided at a later stage

5.1.2 OPEX – Operational costs in Euros per kWh produced [€ /kWh]

Data to be provided at a later stage

5.1.3 Lifetime – Economic useful lifetime of converters in [years]

5.2 Underlying assumptions

As above

5.3 Methodology for data gathering

All data on lifetime projections are based T&D Europe experts' assessment .

5.4 Conclusions on robustness of the produced data

See 2.5 above

6 Environmental impact and public acceptance

6.1 Variables selected

6.1.1 Land use - surface occupation of the transformer or breaker unit (or any other component) [m2].

Computation: typical surface occupied for the considered equipment.

6.1.2 Noise generation

Computation: dB at 150 meter distance

6.1.3 EMC - electromagnetic field generated by the considered component

Computation: issue or no issue.

6.1.4 CO2 emissions

Computation: issue or no issue

6.1.5 Health and safety - [months on site].

Computation: months on site means the amount of time needed on the site to install the equipment.

6.2 Environmental impact today and in 2050

Transformers and AC breakers can be decommissioned after end of life. It is assumed that the net value of the recycled equipment will be greater than the dismantling costs.

An HVDC plant consists of the following materials to be handled properly at end of life disposal:
Metallic materials

- Construction steel
- Stainless steel
- Cast iron
- Galvanized steel
- Electrical steel
- Copper
- Aluminium

Return to a recycling company.

- Insulating oils
- Sulphur hexafluoride (SF6)

Shall be recycled or sent for destruction in line with environmental agencies.

- Cellulose (paper and wood): to be sent for incineration at very high temperature.
- Silicone: to be sent for incineration at very high temperature.
- Glass fibre, laminated. Should be sent to landfill.
- Drying agent. Sent for destruction.
- Other Components. The components should be taken care of in view of the content.

Although manufacturers are continuously working to reduce the environmental impact, specific figures are very hard to predict at this stage.

6.3 Methodology for data gathering

All data on environmental aspects are based on T&D Europe experts' assessment

6.4 Conclusions on robustness of the produced data

The technology covered in this report has a high degree of maturity and has been available for a long time. One can easily determine the audible noise and the losses as the two major concerns and that is also stated above. The maturity and the development speed ensure that the data produced is robust.

7 Market and supply chain issues

7.1 Variables selected

7.1.1 <u>Market issues - cumulated number of units installed [Nb.].</u>

Computation: existing market studies.

7.1.2 <u>Operation experience - cumulated number of years in operation for a given equipment [Nb.].</u>

Computation: starting date is the first integration of the technology by a TSO (corresponding to a TRL of 9)

7.2 Underlying assumptions

Please, see section 2.3.2.

7.3 Methodology for data gathering

All data on market projections are based T&D Europe experts' assessment

7.4 Conclusions on robustness of the produced data

See 2.5 above

8 Dynamic performance of technology

8.1 Variables selected

8.1.1 Phase shifting transformers

No variables applicable for improving the dynamic performance of the technology have been indentified.

8.1.2 Transformers with tap changers

Depending on advancement in technology new materials and or solutions may be available to improve the tap changer functionality and windings.

Computation: commercial availability of improved tap changers [Available/Not available

Computation: commercial availability of superconductivity material for windings [Available/Not available

8.1.3 AC breakers

It is foreseen that advancement in technology will provide new materials and or solutions to have SF6-free breakers and enhanced drive systems.

Computation: commercial availability of SF6-free breakers [Available/Not available

Computation: commercial availability of enhanced drive systems [Available/Not available

8.2 Underlying assumptions

Please see section 2.3.2.

8.3 Methodology for data gathering

All data are based T&D Europe experts' assessment.

8.4 Conclusions on robustness of the produced data

Since all of this technologies has a low degree of dynamic performance very little data is given. The produced data is though robust since this covers mature products.

Bibliography

The main reference is T&D expert competence pool